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SAFEGUARDS AGAINST INTERRUPTIONS OF SUPPLY

By H. W. CLOTHIER, Member, B. H. LEESON, Member, and H. LEYBURN, B.Sc., Associate Member.

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SUMMARY

The paper is intended to present a perspective of the safeguards that have an economic utility in a supply system to ensure an uninterrupted supply of electricity to consumers. The safeguards are classified broadly under the headings of general, routine, protective, and ultimate. Although the most consistent application of general and routine safeguards can never completely eliminate the risk of faults, the appropriate blending of these with protective safeguards, which isolate faults automatically in their initial stages, should prevent any fault from developing into a breakdown of the major order, such as to involve the functioning of ultimate safeguards.

After a general discussion of the application of protective safeguards to supply systems according to whether they include cables or overhead conductors (which, owing to differing conditions, have to be dealt with differently), there follows a survey of protective safeguards available for use with various components of a supply system against short-circuits, transient faults, and excess voltages. These include feeder and busbar-zone protective systems; methods of reducing unnecessary outages of overhead lines; and rapid operation of circuit breakers. Particulars are given of high-speed small-oil-volume circuit breakers developed on the lines of utilizing in improved ways well-tried principles and components, and of an automatic reclosing 132-kV oil circuit-breaker with an arc duration of one cycle at full rating.

It is claimed that, when a fault has developed in a component of a supply system provided with protective safeguards such as automatic instantaneous protection and fast-acting circuit breakers, the result is a switching operation with very little if any damage of the faulty component, and, depending upon the system layout, an outage with either no interruption or only a slight interruption of supply. If, however, a fault develops in an unprotected component of a supply system, the sustained feeding of power into it may lead to severe breakdown and fire, with risk of serious interruption of supply.

The authors suggest that, if the supply industry is of the opinion that it is detrimental to have such interruptions of supply as have occurred in the past (for example, because of outages from transient faults on overhead lines or because of outages due to fires resulting from sustained arcing on unprotected apparatus), and that such interruptions are an uneconomic risk for the future, one of the first steps to be taken is a consideration of safeguards adequate to prevent them.

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(1) INTRODUCTION

Development in the electrical industry depends to a great extent upon experience gained in practice, some fortunate and some unfortunate; and methods well thought out to deal with conditions that existed when they were first applied may, as time goes on, prove inadequate when more onerous conditions arise.

The increasing dependence of the public and industry upon electricity and their increasing consumption of it have brought about more exacting demands, not only for a cheap but also for an uninterrupted supply. In consequence, the safeguards against interruptions, without which neither economy nor continuity is possible, have become of greatly increased importance.

In this paper a survey is made of the safeguards against interruptions of supply available at the present time, and an attempt is made to put them into a proper perspective so that they may be used most effectively and bring about the desired overall economy in supply. Two factors that accentuate the need for safeguards are, first, the increasing growth and interconnection of generating plant, which lead to increased risk of serious damage on the occurrence of a fault, and, second, the increasing tendency to faults occasioned by the extended use of overhead lines for long-distance interconnection and rural-area supplies.

As to the first factor, faults that are rapidly isolated by automatic protection and circuit breakers have come to be regarded as incidents in normal operation, whereas faults not so guarded against, and hence allowed to persist for some time, have become responsible for material damage and dislocation of supply. Such experience points to the value of three major considerations: the foremost is the provision of general and routine safeguards with a view to preventing faults; next, protective safeguards to isolate faults rapidly, should they occur, with little or no damage; and finally, if major damage is inevitable, ultimate safeguards to limit it as much as possible.

The second factor brings about the need for protection against transient faults on overhead lines and against faults caused by excess voltage transmitted from overhead lines to station apparatus. Overhead lines, involving, as they must, exposed conductors, are the most prolific source of faults, and, notwithstanding a preference for cables, an increasing number of distribution systems are bound, under present economic conditions, to adopt overhead lines. Some faults on overhead lines, although harmlessly transient, may lead to unnecessary outages, an outage being an automatic disconnection of a faulty component that may or may not involve an interruption of supply to consumers; but since an outage may be the first step towards interruption, the possibility of clearing faults on overhead lines without outages is obviously a great advantage.

In view of the multiplicity of the components of a supply system, the large number of fault conditions under which they operate, and the variety of the faults that may occur, it follows that safeguards of many kinds are required to meet all contingencies. The question arises for many of them whether they should be brought into action automatically or manually; and the answer depends on their nature and on their sphere of application. For some of them it is effective to make their action dependent upon verbal orders—for example, from a control room; but it is intended that the safeguards described in the paper as protective should be immediately operative in an emergency, and for this reason it is best to make them automatic.

Automatic safeguards may be regarded as a form of decentralized control that stores up in readiness for immediate use operations carefully planned beforehand by supply authorities as best calculated to deal with anticipated emergencies, and ready to be put into practical effect at the critical moment with much greater speed, precision, and reliability than would ever be possible if they were performed manually. With the aid of such automatic safeguards not only is the supply network protected against risk of serious damage, but there is the further advantage that the engineers responsible are relieved of much unnecessary thought and worry during the trying time of a disturbance of the supply system. They are thus left free when most needed to devote their attention to duties associated with restoration of normal conditions and other matters demanding the careful and yet rapid consideration, judgment, and exercise of skill, of which they alone are capable.

(2) SAFEGUARDS AGAINST INTERRUPTIONS OF SUPPLY, AND CONSIDERATIONS DETERMINING THEIR APPLICATION

Fig. 1 shows in diagrammatic form the various safeguards. The components of the supply system to which the safeguards are applied are enumerated at the top of the diagram, and the operating conditions under which they have to be safeguarded are stated immediately below.

(A) General Safeguards (Design, Layout, etc.)

The first general safeguard is the installation of reliable components of adequate rating and performance proved by actual tests under conditions of severity specified in an appropriate standard specification, and not less stringent than those that can occur in service.

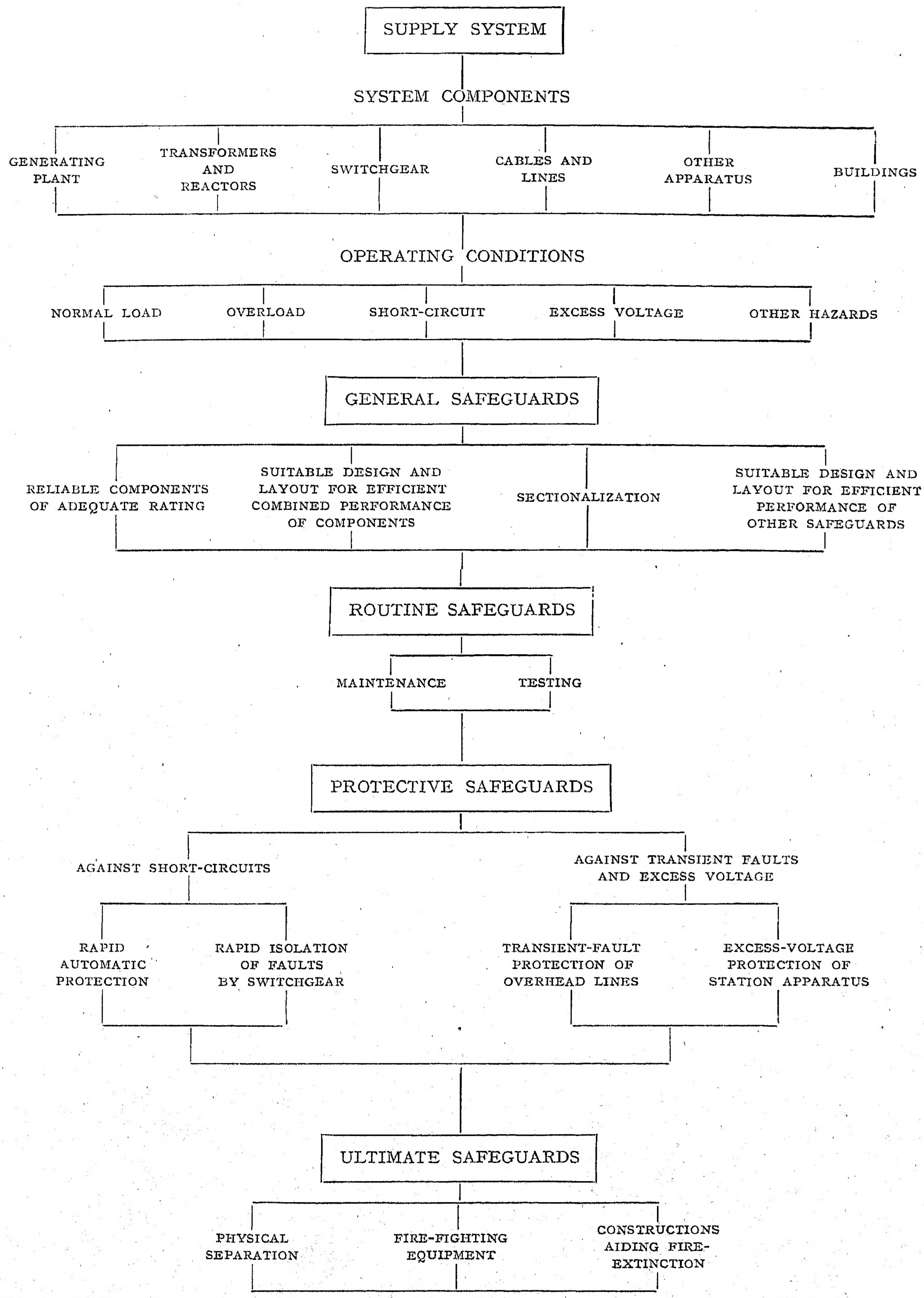


Fig. 1.—Classification of safeguards for a supply system to ensure general economy in operation by the prevention of outages and interruptions of supply.

Reliability may be promoted in many different ways; one of great importance may be mentioned, namely the enclosure of all live conductors, whenever possible, with a view not only to preserving life from the risk of shock but also to avoiding interference with insulation by foreign matter and to preserving the dielectric stability of the surrounding medium. If, as with overhead lines and terminals, such enclosure is not applicable, there is greater need for protective safeguards.

The second general safeguard consists in suitable design and layout of components in order to obtain the most efficient combined performance. A well-planned supply system should include, for example, such features as the electrical sectionalization by switching and by discriminative protective gear necessary to ensure supply to each distributing centre. Voltages for transmission and distribution are best chosen to ensure that the normal-load currents and short-circuit currents shall not attain values that prevent economical design, manufacture, and use, of components like switchgear, protective systems, and cables. In circuit breakers, for example, modern testing-station experience has been instrumental in establishing suitable relations for safety and economy between ratings of breaking capacity, service voltage, and normal-load current, and circuit breakers are being standardized accordingly. It is found, amongst other things, that breaking currents of about 44 000 symmetrical r.m.s. amperes, and corresponding making currents of about 110 000 peak amperes, should not be exceeded at any voltage; that at the higher voltages the current limits should be lower; and that normal load currents should not exceed 2 000 amperes per circuit. The way in which the layout of a network is affected by such relations is shown in greater detail in Table 1.

Table 1

Data Based on Results of Short-Circuit Testing-Station Experience with Switchgear to Illustrate the Way in which the Layout of a Network is Affected by Relations between Service Voltage, Maximum Permissible Short-Circuit at any Point of a Supply System, and Normal-Load Current

Service voltage (kV)	Maximum permissible short-circuit at any point of supply system			Range of normal-load current (r.m.s. amperes)
	Symmetrical 3-phase MVA	Symmetrical r.m.s. amperes (breaking current)	Peak amperes* (making current)	
3·3	250	43 800	112 000	400 – 1 200
6·6	500	43 800	112 000	800 – 2 000
11·0	750	39 400	100 000	800 – 2 000
22·0	1 500	39 400	100 000	800 – 1 600
33·0	1 500	26 300	67 000	400 – 1 200
44·0	1 500	19 700	50 000	400 – 1 200
66·0	2 500	21 900	56 000	800 – 1 200
88·0	2 500	16 400	41 800	600
110·0	2 500	13 100	33 400	600
132·0	2 500	10 900	27 800	600
165·0	2 500	8 760	22 300	600
220·0	2 500	6 570	16 700	600

* Peak amperes = symmetrical r.m.s. amperes $\times \sqrt{2} \times 1 \cdot 8$.

To take a further example, cables have to be selected of such sizes that they will carry not only normal-load currents but also, like other components, short-circuit currents for the times during which faults are allowed to persist,* and they must be capable of doing this without sustaining even incipient damage—for example, by the formation of voids from mechanical or thermal causes—that may bring about breakdown sooner or later. Although short-circuit and other tests are still necessary to furnish the requisite data of cable properties, the problem of correlating cable-sizes with magnitude and duration of short-circuit current has been studied theoretically, with the results shown in Fig. 2. It was assumed that the short-circuit current was carried once only, corresponding to only one break-duty of a circuit breaker; a larger number in rapid succession would indicate the need for greater size of cable. Further, no allowance was made for possible initial asymmetry of the short-circuit current; but, on the other hand, current-decrement was also not allowed for. The curves of Fig. 2 relate to paper-insulated lead-covered single-core cable, and indicate the sizes required to carry short-circuit currents satisfactorily on the basis of an initial tempera-

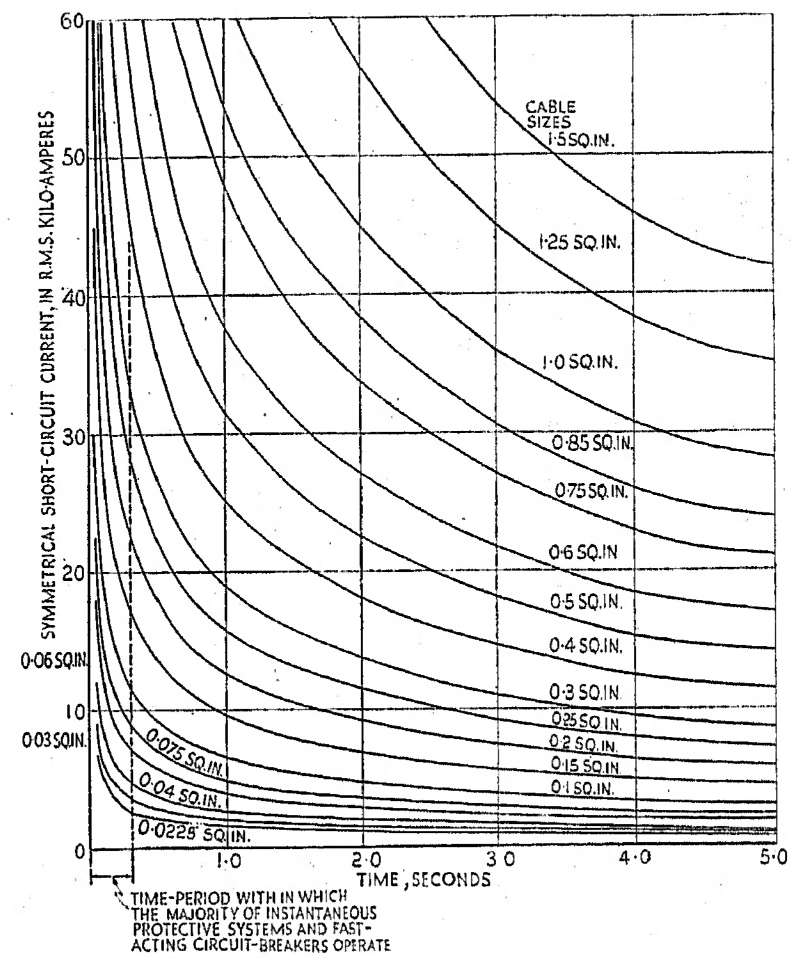


Fig. 2.—Diagram illustrating in principle the relation between cable-size and magnitude and duration of short-circuit current, and indicating the economy in cable-size obtainable by using protective apparatus that isolates a short-circuit instantaneously.

* Cf. J. Eccles: *Journal I.E.E.*, 1937, vol. 81, p. 243.

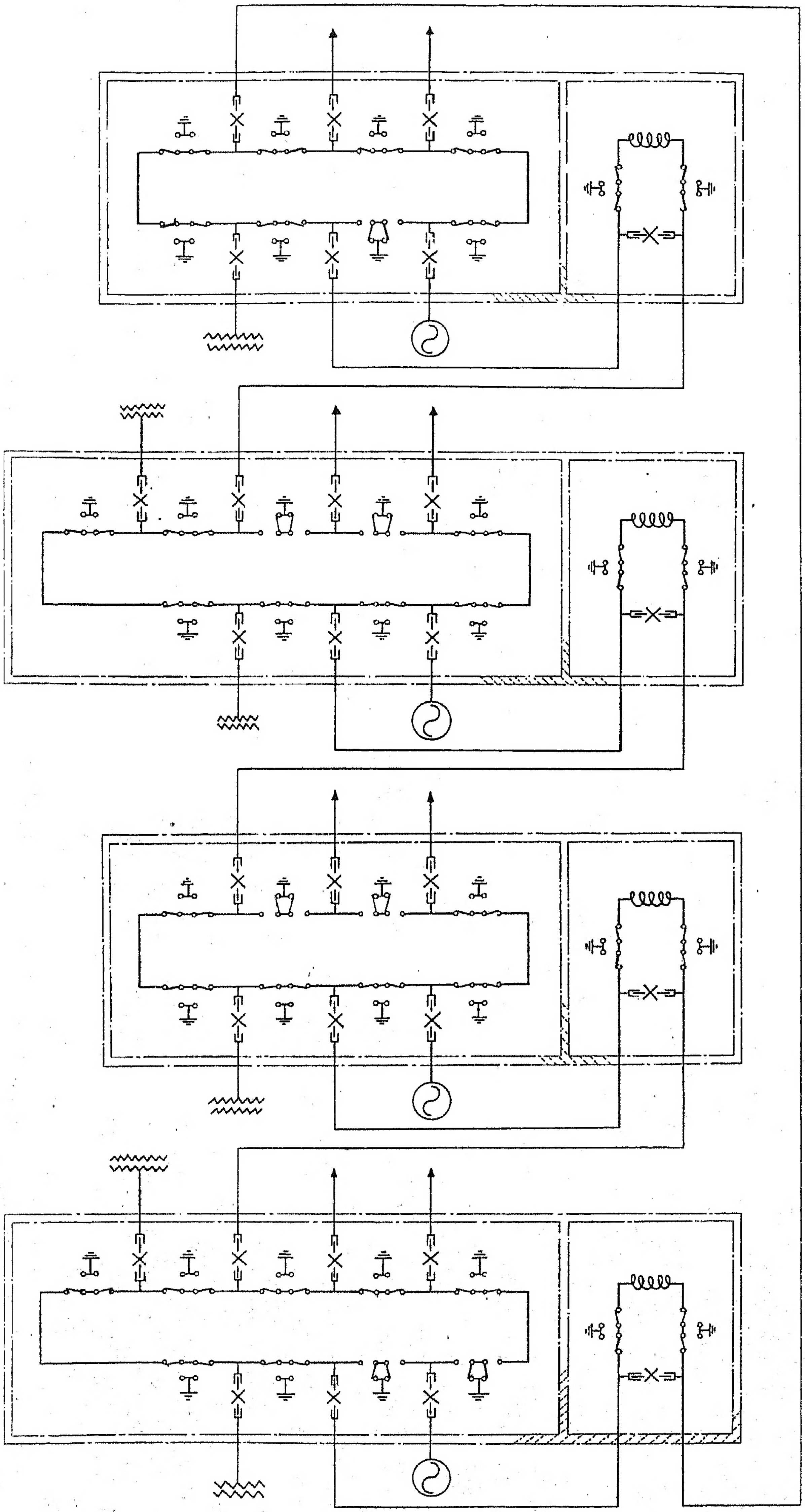


Fig. 3.—Single-line diagram illustrating the layout of a switchgear installation for a major power station planned to provide the general safeguards of Fig. 1, including, for example, electrical sectionalization and physical separation.

KEY TO SWITCHGEAR

Plug isolator

Duplex busbar-section isolating switch — CLOSED — OPEN AND EARTHED

Single-break circuit-breaker

ture of 65° C. and a maximum peak temperature of 120° C. It may be found, after suitable short-circuit tests have been made, that higher temperature-limits for fractions of a second are permissible, and that cables of various types may have different temperature-limits. Since the total time required to clear a fault is determined by the speed of operation of a protective system and a circuit breaker, it follows that the more slowly these operate to clear a fault the larger the cable must be; and hence the use of instantaneous protective systems and fast-acting circuit-breakers can effect a considerable permissible temperature-rise on short-circuit has to be chosen, the authors suggest that particular care should be taken to ensure that faults will start in all apparatus as limited earth-faults only. This can be done in cables, for example, by using preferably single-core cables or, alternatively, a 3-core cable with an earthed conductor surrounding each phase conductor, and in this way the probability that the maximum short-circuit current will occur in practice is rendered remote, provided that between-phase faults are not likely to develop in connected apparatus.

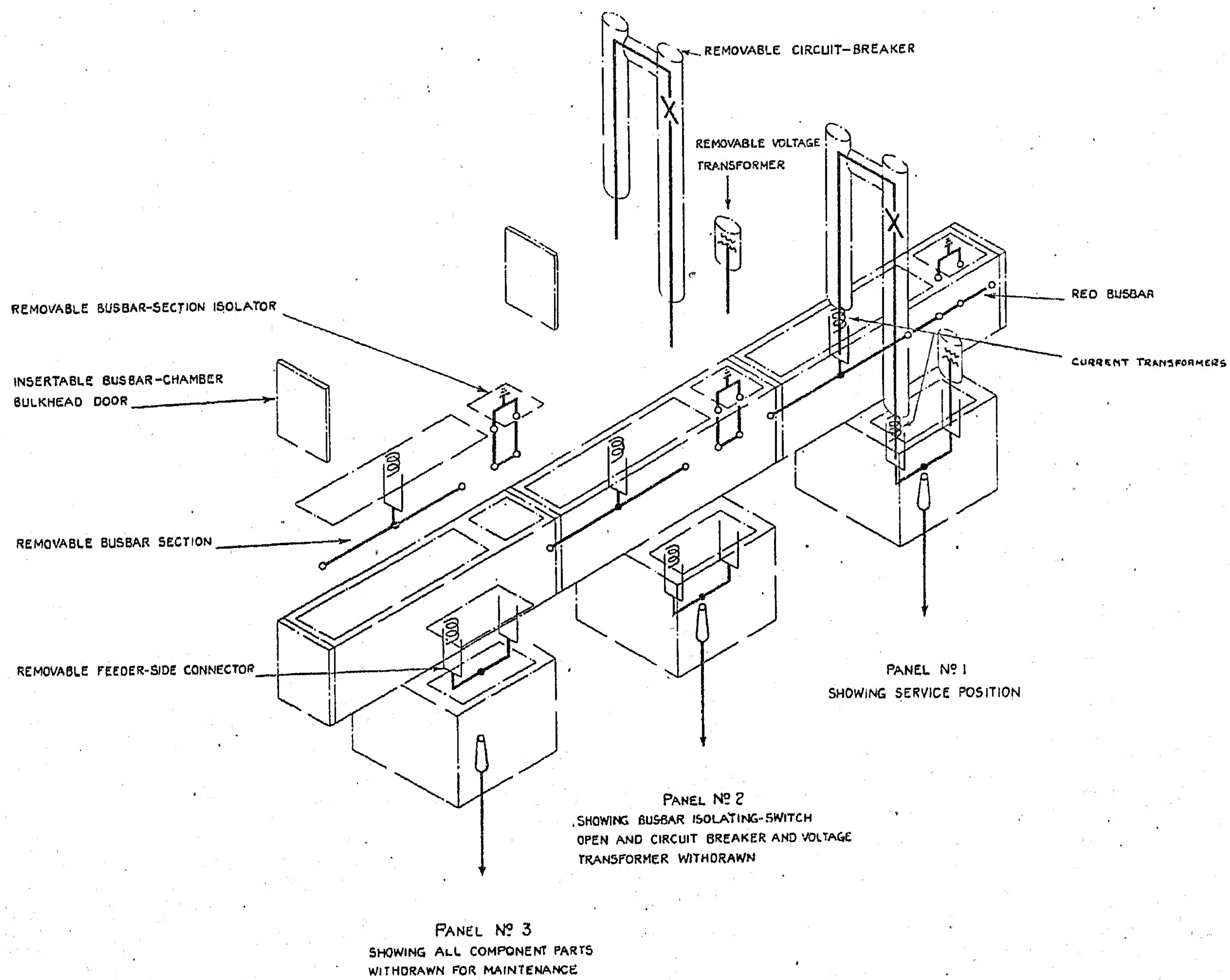


Fig. 4A.—Isometric diagram of one phase of 1 500-MVA 33-kV metalclad switchgear suitable for use in a layout on the lines of Fig. 3, indicating accessibility of components.

economy in the size of the cables necessary for reliable service, taking short-circuit conditions into account. Fig. 2 also illustrates the relatively large sizes of cables that may be required for long life when selected on the basis of short-circuit currents; and hence the need for the limitation of short-circuit currents in a supply system may be even more important for cables than for switchgear.

Should it be found impossible when planning extensions of a supply system to limit the short-circuit current to a value that will allow a cable of economic size to be used, and if consequently a smaller size than that indicated by

The third general safeguard is sectionalization, and the fourth is suitable design and layout for the efficient performance of routine, protective, and ultimate safeguards, including the provision of reliable interlocks for the prevention of other hazards by ensuring correct sequence of operations. Sectionalization and physical separation of both main and auxiliary equipments are important, since they allow components to be isolated for the application of routine safeguards or under fault conditions.

General safeguards of a supply network must necessarily be considered in the early stages of design, and, as

examples of such forethought applied to a switchgear installation for a major power station, Fig. 3 illustrates a layout planned to enable all the safeguards mentioned above to be included, and Figs. 4A and 4B indicate the principles of the construction of 1 500-MVA 33-kV and 66-kV metalclad switchgear designed in accordance with the layout of Fig. 3 and incorporating facilities for access to each component.

materially in detecting incipient insulation breakdowns, but there are inherent limitations and difficulties of application that prevent site testing from becoming a general and effective safeguard. The purpose of insulation site-testing is to discover whether there are any weak spots in the insulation as a whole, and the tests may be classified as (*a*) over-voltage tests and (*b*) quality tests.

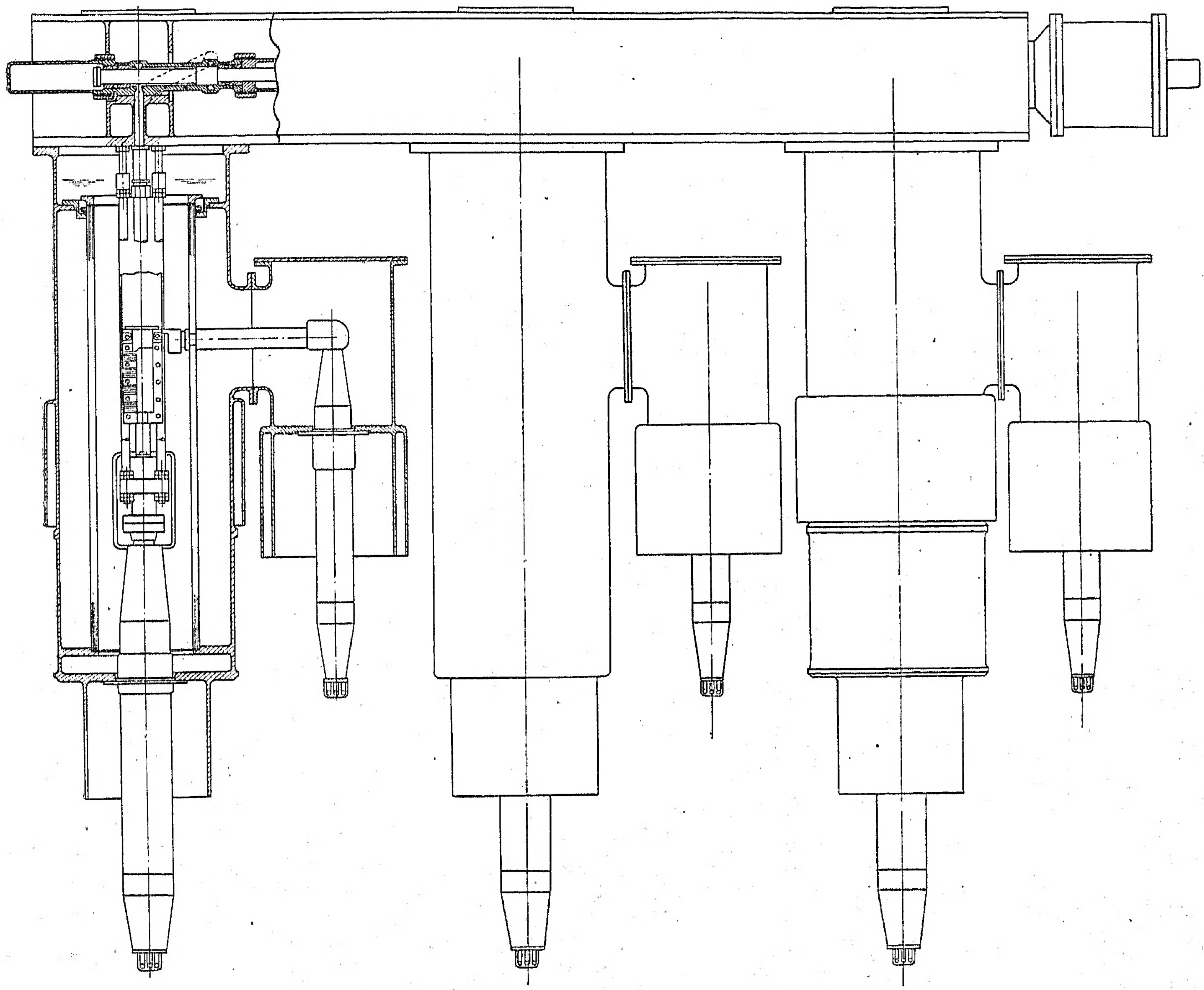


Fig. 4B.—Assembly of the single-break high-speed three-phase oil circuit-breaker with single-break turbulator and pneumo-oil operation as used in the switchgear of Fig. 4A.

(B) Routine Safeguards (Testing and Maintenance)

Routine safeguards include measures taken when a supply system is in operation, and consist primarily of periodical maintenance and testing designed to ensure upkeep of quality and reliable working of components.

There are many well-established routine safeguards, but routine site-testing of insulation is now receiving a good deal of attention as a possible additional precaution, and much may be said both for and against it. When conditions are favourable, some site tests may assist

(a) Over-voltage tests.

Over-voltage tests deliberately stress the insulation as a whole by the application of an over-voltage to detect incipient weak spots, and unless an actual breakdown occurs it is not possible to say more than that the insulation has stood such-and-such a voltage. But the repeated application of an apparently unharmful over-voltage may actually strain unduly and thereby weaken both sound and weak portions of insulation, and it cannot possibly indicate in itself that this has happened. Thus

apparently successful periodic tests do not in reality give any indication of the state of insulation or its probable life. Two typical over-voltage tests are:—

(i) *Alternating-current test.*—The merit of an a.c. over-voltage test is that it reproduces the correct voltage-distribution in the insulation under test; but although it is applicable to components of relatively small electrostatic capacitance it is often difficult if not impossible to apply it conveniently to large-capacitance components, such as cables and apparatus directly connected to them, owing to the size of the testing-equipment required to supply the capacitance current.

(ii) *Direct-current test.*—The merit of a d.c. over-voltage test is that it can be easily applied, since the testing equipment is only required to supply a small leakage-current. It has, however, the serious disability of not reproducing the correct voltage-distribution in the insulation under test, which nearly always includes some form of graded insulation.

Summarizing, it may be said that owing to the fundamental limitations of these two tests, and to the difficulty of establishing suitable test-voltages, over-voltage tests are of little value as routine safeguards to determine the quality of insulation in service, and are useful mainly as initial commissioning-tests.

(b) Quality tests.

Quality tests measure values that indicate quality of the insulation as a whole. Their characteristics vary considerably, and they are therefore dealt with separately below.

(i) *Insulation-resistance test.*—A low-voltage d.c. ohmmeter test applied to high-voltage supply systems gives primarily an indication of quality in respect of insulation resistance or the existence of advanced insulation deterioration bordering on breakdown. Apart from the handiness of a portable testing set for comissioning-tests and for the indication just referred to, the test cannot be regarded as a useful routine site-test for predicting the state and probable life of high-voltage insulation.

(ii) *Power-factor test.*—A power-factor test consists in applying an a.c. voltage (preferably not less than the working voltage) and measuring quantities that enable the power factor of the insulation to be determined. If the results of such periodic tests are recorded and suitably analysed, they enable logical deductions to be made about possible progressive deterioration of insulation. Power-factor tests have been used for many years to determine the characteristics and quality of individual components of insulation during their manufacture; but when they are applied as site tests in service limitations of their usefulness begin to appear. The first of these is that a test can only determine the presence of a weak spot in insulation if the effect on the measurement is sufficiently large to be detected in relation to the effect of the insulation as a whole. It follows that when the effect of a weak spot is swamped by that of the insulation as a whole, as it very often is in practice, the only way of making useful tests is to divide the insulation into parts that can be tested separately. The second limitation, which arises out of the first, lies in the difficulty of finding practical means for dividing up a supply network for the purpose just indicated. Although apparatus installed in the future in major power-stations may provide for complete separation of components for maintenance, as the switchgear illustrated in Figs. 3, 4A, and 4B does, it is unlikely that all the apparatus comprised in a supply network will ever provide such facilities. The third limitation arises out of the need for portability in site-testing apparatus. This sets a limit for both test voltage and electrostatic capacitance, and hence for the size of the component that can be satisfactorily tested. To produce a transportable equipment for power-factor testing, Doble in America has adopted a maximum test-voltage of 10 kV for all system voltages, and his work in stressing the importance of analysing periodic results is well known. A study of the problem leads the authors to suggest that a good compromise between transportability and nearness of test voltage to working voltage is to be found in an equipment with a maximum test voltage of 30 kV, since this would test the majority of supply-system components at or near their working voltage and would at the same time give a nearer approach to the working voltage of the higher-voltage systems.

The merits of suitably-analysed periodic power-factor tests as a useful means of detecting the existence of incipient breakdowns and as a wise precautionary safeguard must be fully recognized, but it is apparent from the considerations just set out that they cannot be regarded as sure and universal means of forecasting insulation-breakdowns.

To sum up generally, the authors suggest that routine site-testing of insulation by the introduction of over-voltage tests is undesirable, but that power-factor tests within their limitations may be useful as a routine safeguard. The need for periodic insulation-testing depends upon many factors, and diminishes with increasing adequacy of protective safeguards.

Site testing must necessarily rank as secondary to the all-important general safeguard of the initial provision of insulation thoroughly proved by testing in the various stages of its manufacture. It can never take its place.

(C) Protective Safeguards (Automatic Isolation of Faults, etc.)

The vital safeguard of a supply system if one of its components develops a fault is the immediate detection of the faulty component by an adequately-rated discriminative protective-system, and its rapid isolation by switchgear of short-circuit ratings proved by tests and suitable for service requirements. Although continued improvement in the quality of component apparatus and its careful maintenance and routine testing result in a reduction of faults per unit during its life, extensions of a supply system frequently increase the number of units installed at a greater rate than the number of faults per unit decreases, and in this way the total number of faults in a supply system usually increases.

Experience proves that the root cause of fires and explosions is uncontrolled sustained arcing. If a fault develops in a component of a supply system provided with protective safeguards, such as automatic instantaneous protection operating in conjunction with fast-

acting circuit-breakers, it is isolated so rapidly that the outage occurs with very little if any damage of the faulty apparatus, and either no disturbance or only a slight disturbance of the supply system. But if the fault occurs in an unprotected component, and hence is allowed to persist, the uninterrupted feeding of power into it causes sustained arcing that not only leads to serious damage of the component from the fault-arc itself as a source of fire and to the possibility of damage of adjacent apparatus but also provides an insidious cause of breakdown of other components, and this sequence of results can bring about a serious interruption of supply. Although the construction of the unprotected component may materially are not affected, (*b*) the use of constructional aids to fire-extinction such as the running of cables in trenches filled with pebbles, and (*c*) the provision of fire-fighting equipment brought into action either automatically or manually.

At this stage it is well to consider the fundamental factors that determine whether or not an electrical fault will result in a fire, and hence whether or not ultimate safeguards must be provided to cope with it. It has been demonstrated that it is the magnitude and duration of the current in an uncontrolled fault-arc that determine whether or not fire eventually breaks out. The magnitude of the fault current may be kept within safe limits

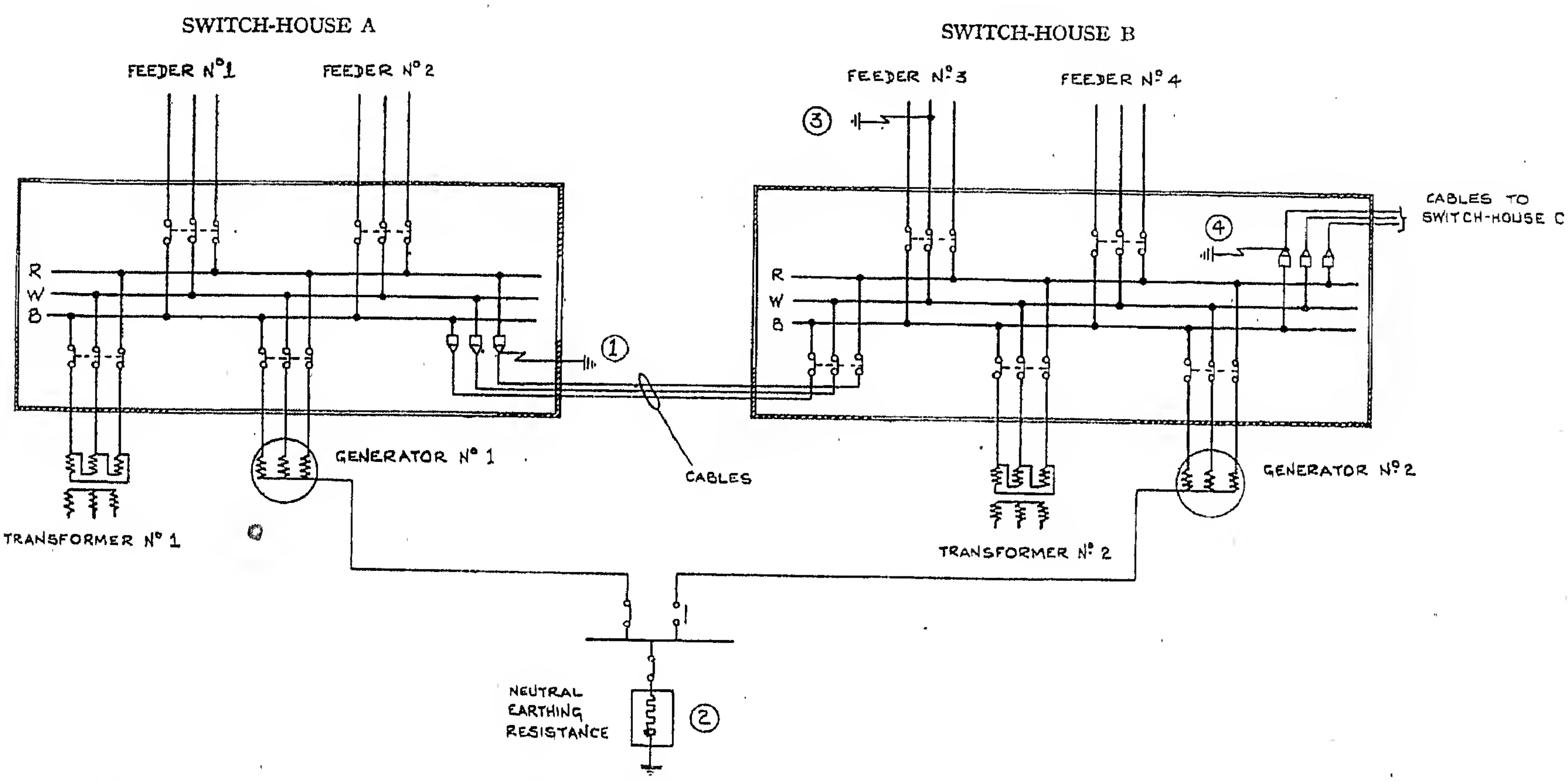


Fig. 5.—Diagram illustrating how a fault in an unprotected zone of one section of a physically separated supply-system can be the cause of consequential faults in other sections.

KEY

Encircled numbers indicate possible sequence of events.
(1) Fault develops on red phase in unprotected zone (e.g. cable box) in Switch-house A, and persists, causing serious damage.
(2) Neutral earthing-resistance, if protected, is isolated; if not protected, it burns out. In either event, system oscillations due to loss of neutral, in combination with persistent arcing of original fault, cause risk of consequential faults.
(3) Consequential fault develops on white phase in the protected zone of Feeder No. 3 and is automatically isolated, causing only slight damage.
(4) Another consequential fault develops on blue phase of unprotected zone in Switch-house B and by its persistence causes serious breakdown and complete shutdown of both switch-houses.

assist in restricting the damage done by the persistent fault, the authors consider it essential in the interests of operating efficiency that any component of a supply system should be rapidly isolated if it becomes faulty.

Since protective safeguards are of fundamental importance, they will be dealt with more fully in Sections (3), (4), and (5).

(D) Ultimate Safeguards (Fire Precautions, etc.)*

Ultimate safeguards, intended as a last line of defence for preventing the spread of damage from faulty apparatus or other hazards, include (*a*) the physical separation of power-station or substation apparatus in such a way that if one section is seriously damaged adjacent sections

* Cf. F. C. WINFIELD: *Journal I.E.E.*, 1937, vol. 81, p. 289.

in practice by so designing the supply system and its apparatus that faults originate as limited earth-faults, i.e. by applying general safeguards; and its duration may also be kept within safe limits by applying automatic protective safeguards.

It is the lack of general, routine, and protective safeguards that largely brings about the need for ultimate safeguards, which by themselves, it must be said, have definite limitations. For example, although the physical separation of switchgear with unprotected busbar zones into two switch-houses, as shown in Fig. 5, prevents the direct communication of fire from one house to the other, it cannot prevent the spread of electrical causes of fire by consequential faults as long as the electrical interconnections are not interrupted. This interruption can be effected with sufficient speed only by protective safe-

guards applied to all components, including busbar zones.

These considerations lead to the conclusion that although the provision of ultimate safeguards is desirable they should be regarded only as additional to protective safeguards, so that, instead of having to function frequently, as they would in the absence of protective safeguards, they are required to deal only with extreme emergencies, or with hazards outside the control of the supply industry. In such circumstances they can be applied more economically, and the saving can be used to greater advantage in the provision of protective safeguards.

Much might be said about air-raid hazards, and many kinds of ultimate safeguards not mentioned here may readily suggest themselves. It would appear necessary, however, to limit such safeguards to those justifiable in the interests of economical supply, and to acknowledge the inevitableness of some havoc in the event of an air raid, to be dealt with by emergency measures previously planned.

(E) Application of Protective Safeguards to Supply Systems Including Cables

Since supply systems including cables are not subject to excess voltages caused by lightning or to transient faults, the only problem that arises in such systems, so far as the application of protective safeguards is concerned, is that of protection against short-circuits; and this necessitates rapid disconnection of faulty apparatus.

Two conflicting considerations have to be taken into account in determining how a fault should be isolated; the first is that the fault current must be ample for the operation of the protective gear, and the second is that the same fault current must be kept as small as possible in order to limit consequential damage. The established British practice is to earth the neutral point of a system through a resistance in order to limit a fault current sufficiently to prevent unnecessary damage, but yet to allow the passage of enough current to operate the protective system. Further, by constructing the component apparatus in such a way that faults start as earth faults only, and by providing an instantaneous protective system and fast-acting circuit-breakers, the great majority of faults are cleared as earth faults, with little if any damage of faulty apparatus and no damage whatever of sound apparatus. With earth faults, speed of operation is important; it is even more so with phase faults, in spite of their relatively small number, since a phase-fault current cannot be limited to anything like the same extent as an earth-fault.

Examples of modern unit protective-systems suitable for application to supply-systems including cables are given in Section (3).

(F) Application of Protective Safeguards to Supply Systems Including Overhead Conductors

Fundamentally, the conditions in supply systems including overhead lines are similar to those in systems including cables, except that two additional factors necessitate additional or modified protective safeguards. The first, which is the effect of lightning on component apparatus, makes excess-voltage protection necessary; and the second is that faults in overhead lines, such as flashover of insulators, may be only transient, and if suitably dealt with can be cleared without causing an outage or involving the repair of a faulty insulator. Since transient faults are found by experience to be usually 80 to 90 per cent of the total, or even more, this factor is of great importance, particularly in districts fed by only one line.

The most suitable way of dealing with the protection of systems including overhead lines against short-circuits, transient faults, and excess voltages, would therefore appear to be to use methods for short-circuit protection similar to those in systems including cables, and to add apparatus providing transient-fault protection for overhead lines and excess-voltage protection for station apparatus connected to overhead lines. This question is dealt with more fully in Section (4).

(3) PROTECTIVE SYSTEMS FOR SHORT-CIRCUIT FAULTS

The extensive use in Great Britain of what have been known as instantaneous unit protective systems of the balance type for the protection of generators, transformers, feeders, and other apparatus has caused such protection to be taken almost as a matter of course. The authors use the term " instantaneous " in its commonly-accepted sense indicating rapid operation; but they must point out that, according to a standard definition, it is also capable of meaning that a system is not purposely delayed, irrespective of its actual operating time. In view of possible ambiguity, therefore, they use, in addition, the term " high-speed " in referring to protective systems according to their actual times of operation. Throughout the paper, a high-speed system is one in which the time from the incidence of a fault up to the closure of the contacts energizing the trip coil of the circuit breaker does not exceed 5 cycles at 10 times the minimum operating current. It is to be understood that here and elsewhere in the paper " cycles " are 50-per-second cycles.

Although it is desirable to use high-speed systems whenever possible, systems with longer operating times may often be applied successfully. High-speed systems are preferable for important very-high-voltage overhead transmission lines, such as the 132-kV British grid, connecting together large generating centres, because less-rapid clearance of a fault on such lines has greater effect on a large area, and may lead to system instability.

The reasons requiring instantaneous action of protective systems are twofold. Firstly, the concentration of large generating plant and the growth of networks increase short-circuit currents and kVA to such an extent that very considerable damage may be done if a fault is allowed to persist for any appreciable time, and there is the additional risk that an earth fault may develop into a phase fault. Secondly, there is the possibility that synchronous motors, rotary convertors, and even generating plant itself may fall out of step if a fault is allowed to persist. Little trouble appears to have been experienced in Great Britain because of falling-out-of-step of generating plant, owing no doubt to good design and also to wide use of instantaneous protective systems (some

of which actually have always been of the high-speed type) and resistance-earthing of the neutral. On the other hand, synchronous machinery other than generating plant has been known to fall out of step, and this has become more frequent with the introduction of protective systems having time-lags.

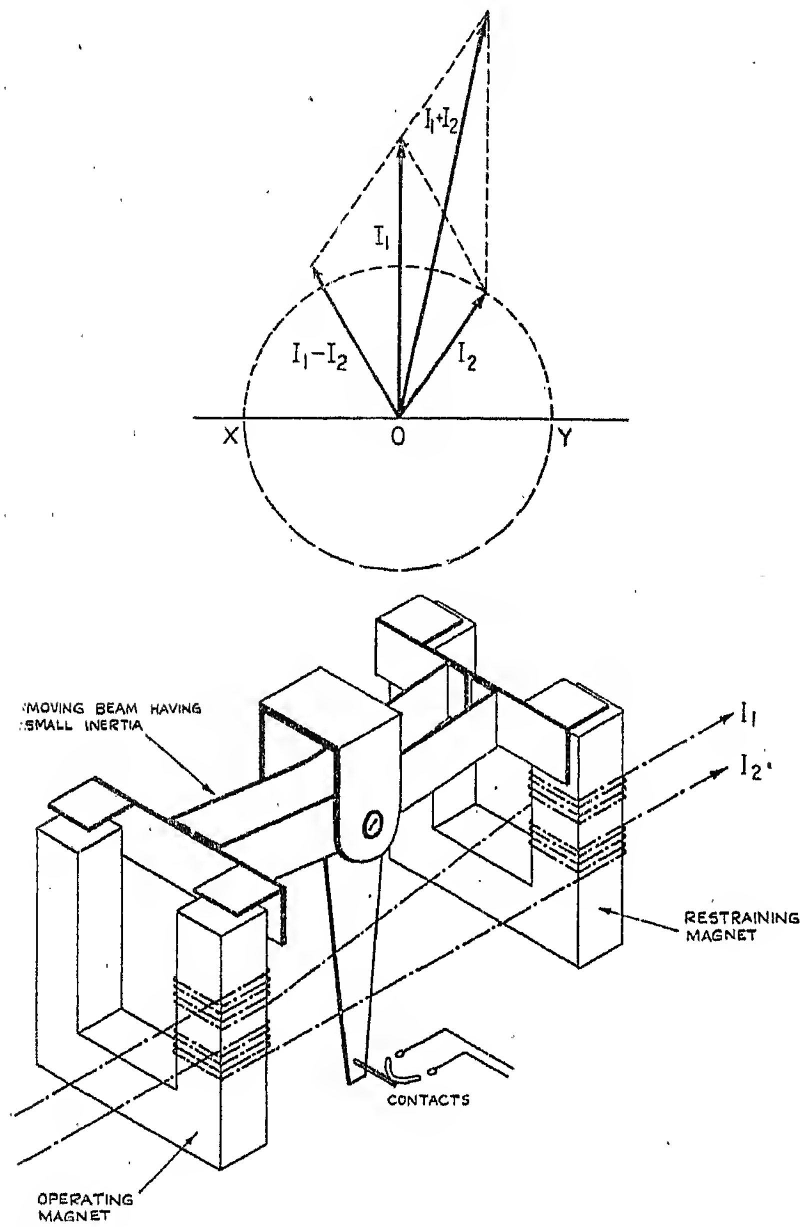


Fig. 6.—Isometric diagram and vector diagram illustrating the construction and operation of an electromagnetic high-speed directional relay.

KEY

I_1 = current in first relay winding.
I_2 = current in second relay winding.
Flux in operating magnet is proportional to $(I_1 + I_2)$.
Flux in restraining magnet is proportional to $(I_1 - I_2)$.
Relay operates and closes contact when $(I_1 + I_2)$ is greater than $(I_1 - I_2)$ i.e. when I_2 is in the same general direction as I_1, namely when the vector representing it lies above the line XOY.
Relay restrains and keeps contact open when $(I_1 + I_2)$ is smaller than $(I_1 - I_2)$ i.e. when I_2 is in the opposite general direction to I_1, namely when the vector representing it lies below the line XOY.

Such considerations of the need for speedy fault-clearance involve also the circuit breakers used with the protective sytem, and in this connection reference may be made to Section (5).

High-speed operation of protective systems is easily obtained with non-directional current-operated relays, but has hitherto been difficult to obtain with directional relays. One way of overcoming the difficulty by using a high-speed electromagnetic movement is illustrated in Fig. 6.

Although it is desirable to clear a fault in as short a time as possible, this must not be done at the risk of possible wrong operation of the protective system. The limiting factors that determine its minimum operating time depend upon the transient phenomena that occur under short-circuit conditions, but their effects differ according to the fundamental characteristics of the protective systems.

With systems of the balance type the minimum operating time is determined by oscillations of the primary supply system, which have a frequency usually well in excess of the third-harmonic frequency. When using a protective relay tuned to the fundamental frequency, as, for example, in the Solkor system mentioned below, there is no reason other than the mechanical limitation of the relay itself why it should not be allowed to operate in, say, one cycle of third-harmonic frequency, i.e. in 0·007 second in a 50-cycle supply network.

The considerations governing the minimum operating time of systems using directional relays are of a different kind, and are due to the transient phase-displacement between current and voltage at the commencement of the fault, particularly when the short-circuit current is asymmetrical. The momentary effect on the relay is that the direction of power flow may be opposite to the true direction, and to ensure correct operation with a factor of safety it is necessary, for example, with the relay of Fig. 6, to increase its operating time deliberately to 1–1½ cycles; and, on adding one half-cycle for the operation of the d.c. repeat contactor, which initiates tripping and which is usually provided in connection with sensitive relays, the total time of operation is 1½–2 cycles.

(A) Examples of High-Speed Feeder-Protective Systems

Progress in the design of balance feeder-protective systems has been mainly in the direction of making them simpler and suitable for less costly pilot cables, whereas in distance and interlock systems improvements have been primarily for securing increased speed of operation. The three feeder-protective systems summarized below represent three main classes, namely balance, distance, and interlock.

(a) Balance.

The Solkor feeder-protective system, illustrated in Fig. 7, is a simplified system of the balance class, and is based on the same principles as the split-pilot system,* which is used for important transmission networks. For economical and practical reasons the Solkor system, which has similar characteristics but uses smaller components and simplified connections, is more appropriate for the shorter feeders in distribution networks. The system uses solid-core current transformers of the instrument type and a plain 2-core pilot cable.

(b) Distance.

The high-speed Ratio-balance feeder-protective system, which is based on the same principles as the original ratio-balance system,* belongs to the distance class, and

* B. H. Leeson and H. Leyburn: "The Principles of Feeder Protection, and their Application to Three Modern Systems," International H.T. Conference (Paris), 1931, Paper No. 106.

is primarily intended for application to long overhead transmission lines. Fig. 8 shows typical time/distance curves relating to this system, which is classified as high-speed because of its operating speed over the greater part of the protected feeder. Although the system can be used to the best advantage in conjunction with high-speed circuit-breakers having total break times not exceeding 5 cycles, it can also be used with circuit-breakers of longer total break times; but under these conditions full advantage cannot be taken of the high-speed operation of the relays, namely in 2 cycles for faults in the instantaneous zone extending over approximately 80 per cent of a protected feeder, and in 10 cycles for faults in the remainder of the feeder.

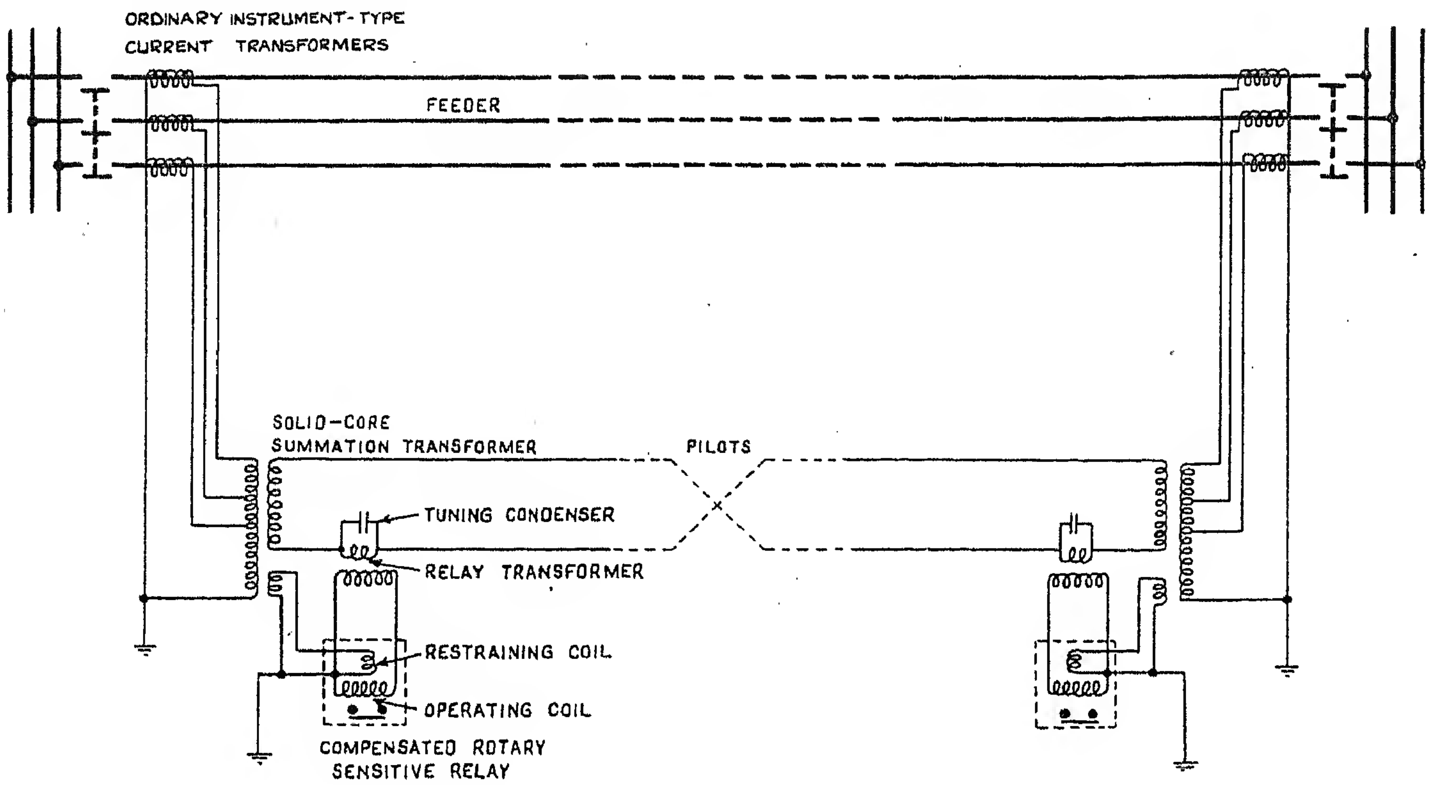


Fig. 7.—Feeder-protective system of the balance class: Solkor system.

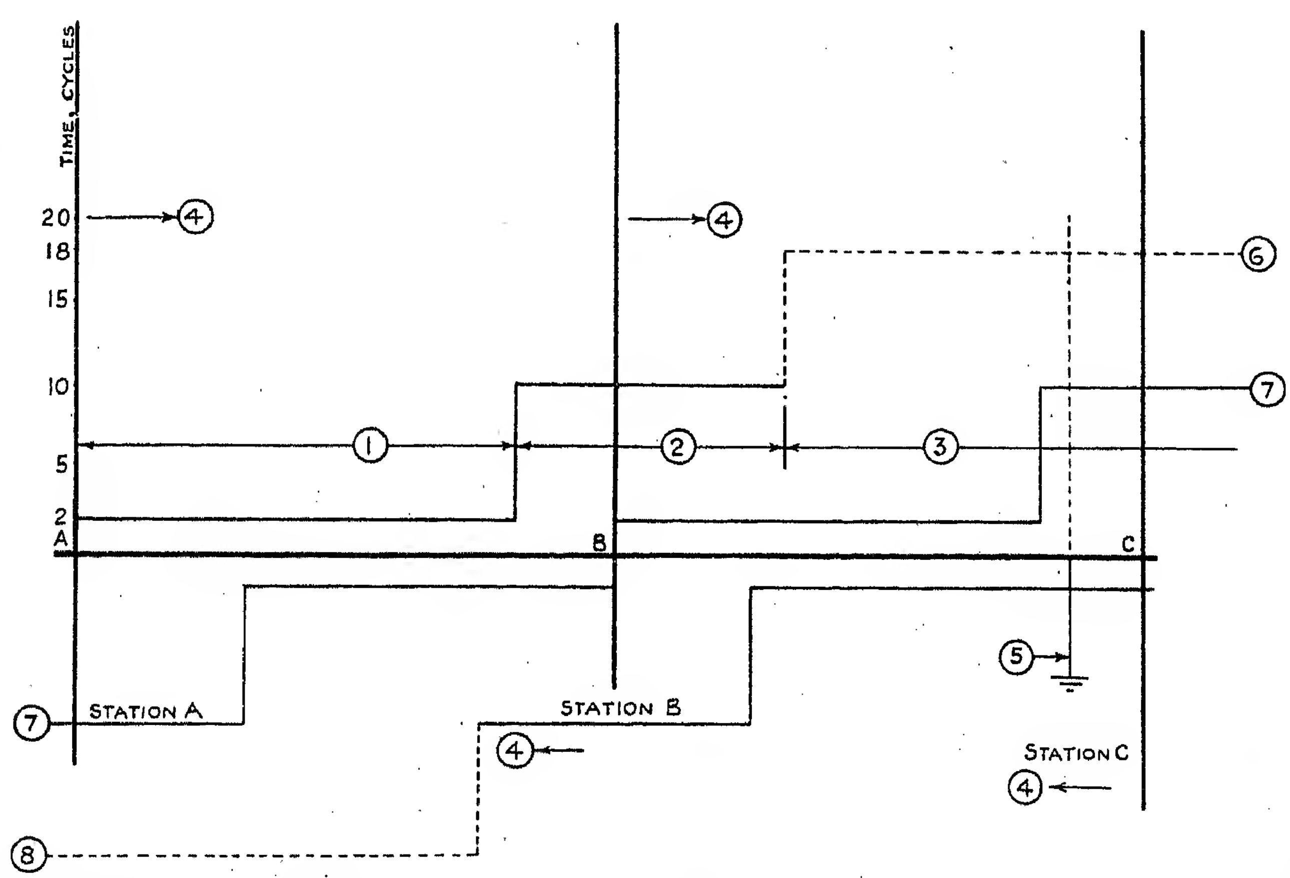


Fig. 8.—Feeder-protective system of the distance class: characteristics of the high-speed Ratio-balance system.

1. Instantaneous zone.
2. Time-discriminating zone.
3. Back-up zone.
4. Direction of power.
5. Position of fault.
6. Characteristic of relay at A.
7. Characteristic of relays at B.
8. Characteristic of relay at C.

In order to obtain greater accuracy of measurement of reactance or impedance in connection with distance protective-systems applied to multiple-earthed networks, a scheme known as "sound-phase compensation" is used. The principle upon which it is based is that a proportion of the current flowing in the two sound phases on the occurrence of an earth fault is injected into the relay coil associated with the faulty phase in such a way that the impedance or reactance measured by the relay is not affected by the current flowing in the sound phases.

(c) Interlock.

Fundamentally, the high-speed superimposed Interlock feeder-protective system operates in the same way as the original Interlock system,* but the operating time

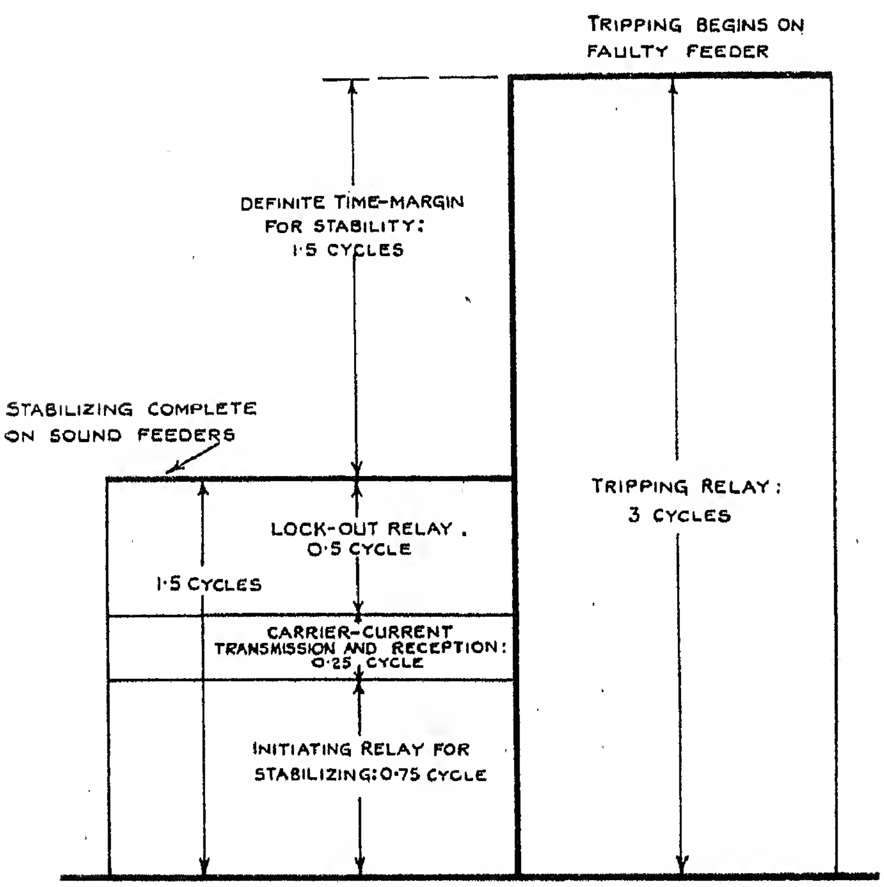


Fig. 9.—Feeder-protective system of the Interlock class: stability diagram of the high-speed superimposed interlock system.

is much shorter. Fig. 9, the stability diagram of the system, shows that a healthy feeder is stabilized in 1·5 cycles, and the tripping of a faulty feeder is initiated in 3 cycles, after the commencement of the fault.

(B) Protective Systems for Generators, Transformers, and Reactors

Although there have been alterations of detail, there has been litle fundamental change in recent years in the systems used for protecting generators, transformers, and reactors, and for this reason it is proposed not to enter into their details but merely to refer to them in order to complete the record of typical protective systems. Broadly speaking, the balance system, being both discriminating and instantaneous, has given satisfactory service, and is widely applicable. A typical exception is the protection of a power transformer with on-load tap-changing, or with a high ratio of transformation, or with a large output at low voltage, when it may be preferable to use over-current and restricted earth-leakage relays protecting the primary and secondary windings separately.

* B. H. Leeson and H. Leyburn: "The Principles of Feeder Protection, and their Application to Three Modern Systems," International H.T. Conference (Paris), 1931, Paper No. 106.

(C) Busbar-Zone Protection

Systems for the protection of generators, transformers, reactors, and feeders have been used widely in practice, and have contributed greatly to the freedom from interruption that has been one of the chief characteristics of the British supply industry; but busbar-zone protection as such has not received much serious attention in Great Britain until recently, although back-up over-current and earth-leakage relays have incidentally been of some limited use in this connection.

(a) Need for busbar-zone protection.

There appears to be a growing appreciation of the need for the extended use of busbar-zone protection brought about by the rapid growth of generating and distributing centres already referred to, and by the recognition that faults in a busbar zone, which is a vital part of a supply system, may have serious consequences unless they are cleared rapidly. The wider application of busbar-zone protection in the U.S.A. and on the Continent is noteworthy.

If the supply industry is of the opinion that such interruptions of supply as have been caused in the past by fires resulting from sustained arcing are regarded as a menace and an uneconomic risk for the future, the authors suggest that one of the primary steps to be taken is the provision of more adequate safeguards against the persistence of fault currents in hitherto unprotected busbar zones, which may extend to interconnecting cables and cable boxes.

(b) Methods of using busbar-zone protection.

When protective safeguards against the persistence of fault currents in busbar zones are being considered it is desirable that the term "busbar-zone protection" should be interpreted in its broadest sense as including not only protective systems for automatic tripping but also systems that may facilitate the manual disconnection of faulty sections. For example, if it is thought that some operating experience should be gained before fully-automatic protective systems are applied, a combination of automatic and manual tripping may be adopted in which the protective relays are connected as described below, but their trip contacts are arranged to give an alarm, and only to prepare the trip circuits of the circuit-breakers controlling the faulty section without actually tripping them. The trip circuits are then completed by the operator, who is instructed to close the appropriate master tripping switch if he is satisfied that a fault is persisting, as may be indicated, for example, by a leakage ammeter mounted in a conspicuous position. In this way a double check in respect of stability is obtained, firstly by the protective system itself and secondly by the operator; and, further, the operator is relieved of undue responsibility, and faults that otherwise might persist for a long time may be cleared in a few seconds.

The logical sequel of the combination of automatic and manual operation described above is that the protective relays should eventually be so connected as to bring about entirely automatic tripping, and in this way they may still further speed up the removal of fault conditions until it is virtually instantaneous, with the great advantage of reduced initial and consequential damage.

The first three of the automatic busbar-zone protective systems described below, namely those in the leakage-to-frame, balance, and balance-interlock classes, are inherently instantaneous in operation. There may, however, be a short overlap region between the current transformers for busbar-zone protection and those for the protection of individual circuits, and this region is therefore doubly protected. It is important that faults should if possible be cleared as circuit faults rather than as busbar-zone faults; and therefore the protective systems should be so arranged that if a fault occurs within the doubly-protected overlap region the circuit protection operates in preference to the busbar-zone protection. Such discrimination can be ensured by adding, when necessary, a short time-lag to the normally instantaneous busbar-zone protective system. The fourth system described below, namely interlock-time, already has an inherent time-lag normally sufficient to ensure correct sequence of operation.

(c) Examples of busbar-zone unit-type protective systems and their application.

Whereas only time-delayed non-discriminative protection is obtained with over-current and earth-leakage relays, as is described later, unit-type protective systems provide instantaneous discriminative disconnection of a faulty section. The zone protected by busbar-zone protective systems includes the busbars themselves, the circuit breakers, the current transformers, and the connections associated with these parts, together with whatever interconnecting cables and cable-boxes there may be, usually up to the point where the busbar-zone protective transformers are mounted.

The four unit systems, each having its own field of usefulness, have been devised to ensure absolute stability under straight-through-fault conditions, which is a fundamental requirement. They are based on the following broad principles: Firstly, two lines of defence against mechanical instability are provided, since at least two relays must operate before the busbars are isolated; and further, in the Dualock system the two lines of defence are in addition quite independent electrically. Secondly, an alarm is given if a fault that might endanger stability develops in the secondary protective circuit, and easy routine testing is provided for. Thirdly, all the circuit breakers controlling a faulty section are tripped on the occurrence of a busbar-zone fault, and, if necessary, all circuits can be disconnected at the remote end. Fourthly, protection against earth faults only is provided, since switchgear construction usually provides that busbar-zone faults originate only as earth faults.

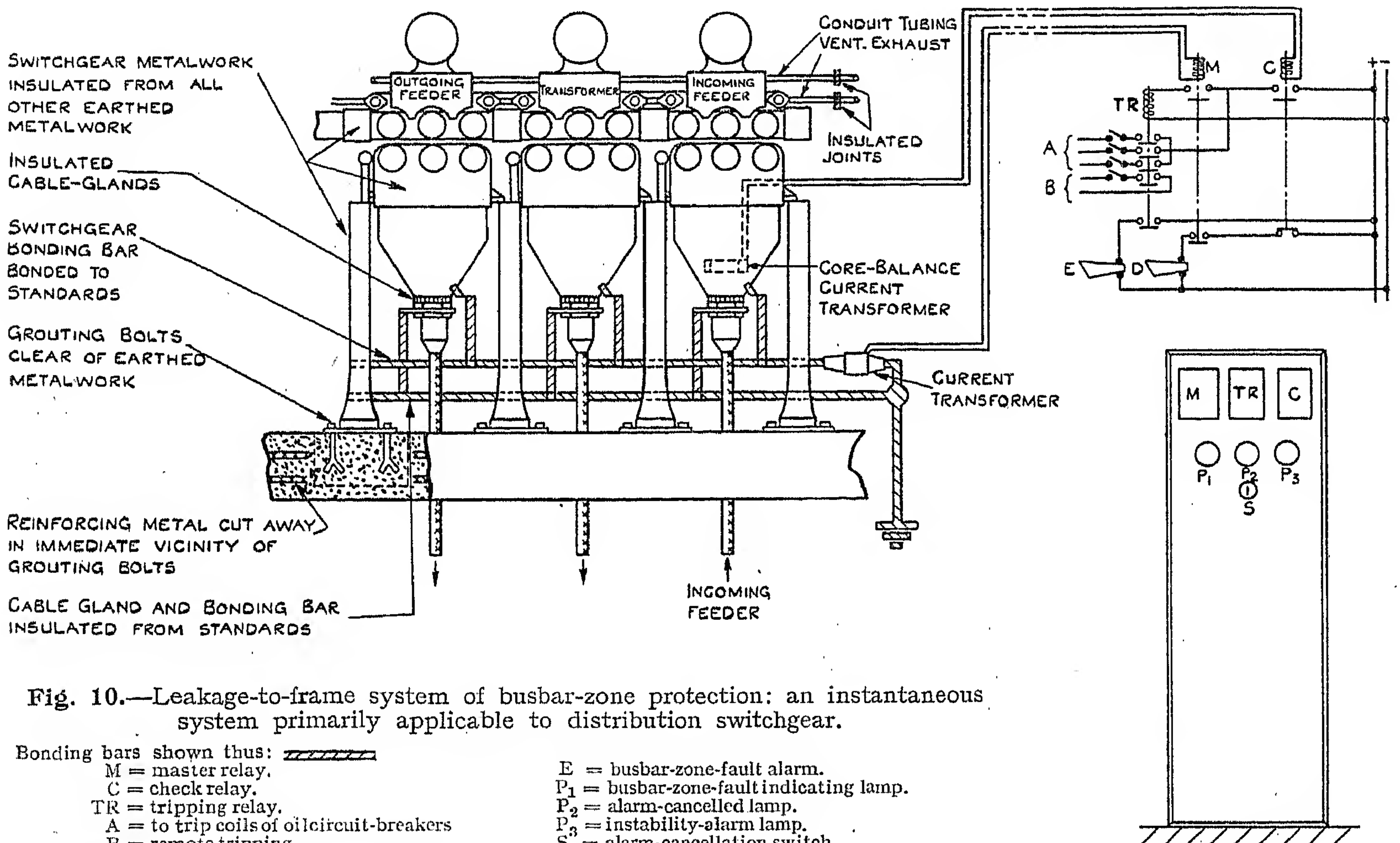


Fig. 10.—Leakage-to-frame system of busbar-zone protection: an instantaneous system primarily applicable to distribution switchgear.

Bonding bars shown thus:
M = master relay.
C = check relay.
TR = tripping relay.
A = to trip coils of oil circuit-breakers
B = remote tripping.
D = instability alarm.
E = busbar-zone-fault alarm.
P_1 = busbar-zone-fault indicating lamp.
P_2 = alarm-cancelled lamp.
P_3 = instability-alarm lamp.
S = alarm-cancellation switch.

(i) *Leakage-to-frame*.—The instantaneous Leakage-to-frame system is illustrated in Fig. 10, and is particularly suitable for new switchgear. It is rarely suitable for existing switchgear owing to the necessity for insulating the framework; and although it is applicable to large switchgear its most useful application is for what may

be called distribution switchgear, say from 75 to 350 MVA breaking capacity.

(ii) *Balance.*—The instantaneous Self-check system, illustrated in Fig. 11, is based on the balance principle. A feature that has been added in order to ensure service continuity, and that gives the system its name, is provision for continuous self-checking of such a kind that, by the operation of a sensitive alarm-relay, a warning alarm is given of any defect in the secondary circuits of the protective system that might cause instability on the occurrence of a straight-through fault. This system is suitable for small transmission switchgear, say from 350 to 750 MVA breaking capacity, such as is used in important substations or small and medium-sized power major power stations and substations because its stability is doubly secured. It also can be applied to existing switchgear subject to the addition of current transformers.

(iv) *Interlock-time.*—In the Time-lock system illustrated in Fig. 13 the balance feature forming part of the instantaneous Dualock system is replaced by a time-lag feature; consequently balanced current-transformers are not required, and existing current-transformers may be used. Hence the Time-lock system is particularly suitable for existing switchgear. Its two lines of defence are; first, a time-lag in the master relay; and second, directional discriminating-relays, one per circuit, which function in exactly the same way as in the Dualock system. In a well-protected network most faults are cleared rapidly,

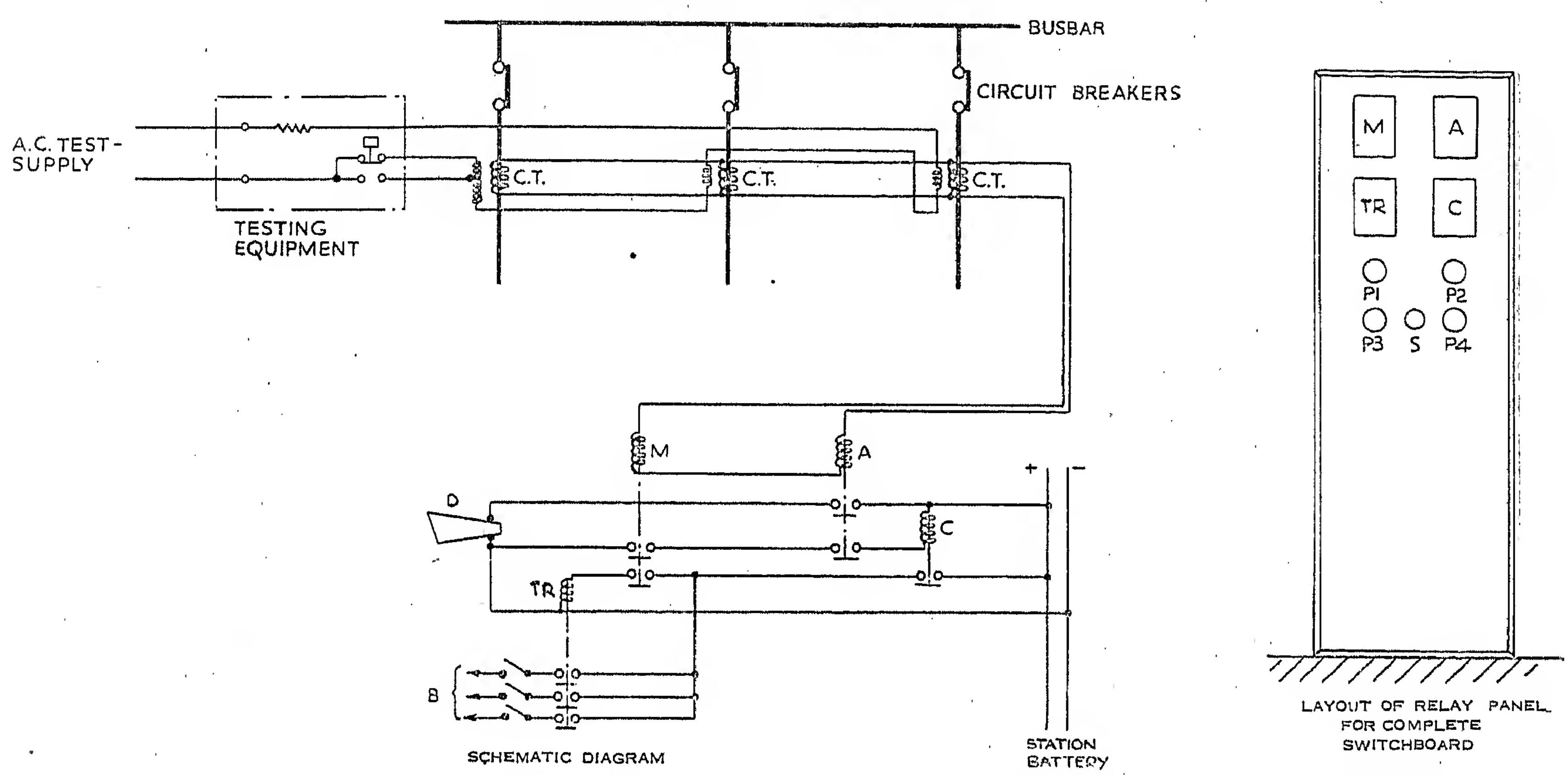


Fig. 11.—Self-check system of busbar-zone protection: an instantaneous system primarily applicable to transmission switchgear—for example, from 350-MVA to 750-MVA breaking capacity.

M = master relay (set higher than A).
A = alarm relay (set lower than M).
TR = d.c. multi-contact tripping relay.
C = main d.c. relay.
P_1 = busbar-zone-fault indicating lamp.
P_2 = testing-supply indicating lamp.
P_3 = alarm-cancelled lamp.
P_4 = instability-alarm lamp.
S = alarm-cancellation switch.
D = busbar-zone-fault alarm.

stations. It can be applied to existing switchgear, and the additional current transformers may be of the clamp-on type, the cable glands being insulated.

(iii) *Balance-interlock.*—The instantaneous Dualock system, illustrated in Fig. 12, has been so named because two entirely independent locking features are provided in order to ensure two lines of defence against instability. These are based respectively on balance and interlock principles, and are so arranged that in the unlikely event of one of them inadvertently operating the other still maintains stability, and it is only when both operate together that tripping occurs. In addition it incorporates a continuous self-checking feature (not shown in Fig. 12) similar to that of the Self-check system, and, like the Time-lock system, eliminates auxiliary switches from current-transformer circuits, where they would be a source of weakness. This system is suitable for switchgear in and hence by giving the master relay a time-setting greater than the ordinary setting of other relays on the supply system it is possible to ensure that for the great majority of external faults it will not close its contacts, and the directional lock-out feature is not called upon to function at all; in the small number of external faults in which the clearance time may exceed the setting of the master relay, the directional lock-out feature by itself ensures stability. Thus the discriminative disconnection of a faulty busbar zone, even though with a time-lag, makes the Time-lock system well worth consideration in existing large power stations, where other forms of protection may be difficult to apply.

(d) Over-current and earth-leakage relays.

If, in view of the comparative freedom from breakdowns in the past, it is considered that the application

of unit-type busbar-zone protective systems to the whole of an existing supply system is not justified economically, there is then a field for some alternative and not too costly means of preventing a busbar-zone fault from persisting indefinitely. In this connection the authors support the use of over-current and earth-leakage relays for the less important stations, since they provide time-lag protection against busbar-zone faults if their settings are based upon the following considerations. The minimum earth-fault current that will flow on the occurrence of an earth fault should be calculated for each busbar zone on the basis of the maximum resistance of the neutral earthing-resistor, and the number of connected feeders that will carry this current should be used to find what proportion of it will flow in each of them. Obviously, only this proportion is available to operate over-current and earth-leakage relays, and the settings must be low enough to ensure operation in as short a time as possible consistent with the necessary discrimination. If over-current relays only were used, it would probably be found, particularly in large stations and those with many outgoing feeders, that the proportion of fault current in each feeder was frequently insufficient to operate them, and hence it is necessary to include earth-leakage relays of the time-lag type, which can be set for lower fault currents.

Although over-current and earth-leakage relays can usually be so set and graded that a busbar-zone fault is disconnected, their use suffers from the disabilities of relatively long time-lag and risk of shutting down healthy stations or busbar sections owing to insufficient discrimination. Although this may not be of serious consequence for the less-important stations, it may result in a complete shut-down if a busbar-zone fault occurs in a major power station or substation, and hence for such stations a unit-type busbar-zone protective system is required.

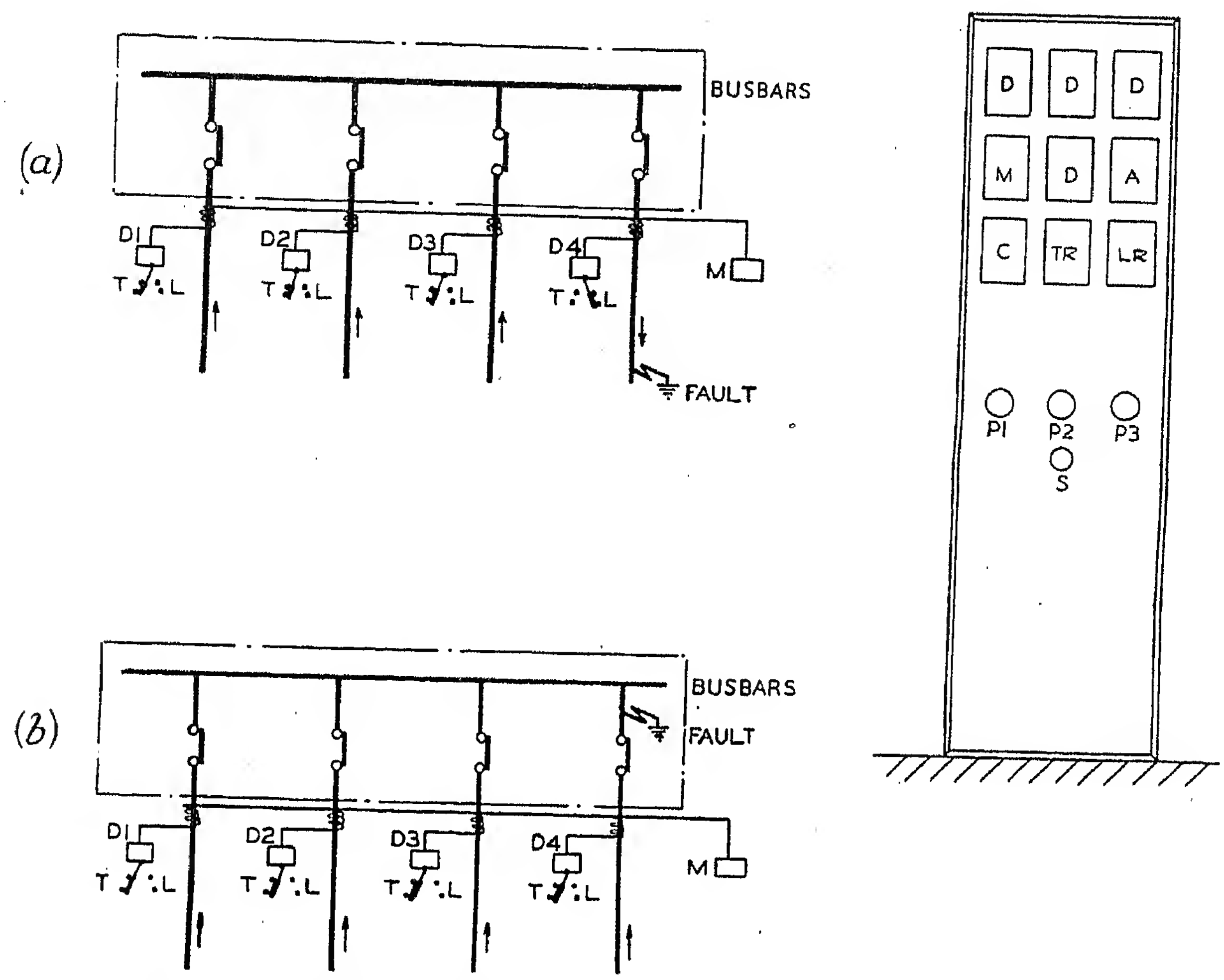


Fig. 12.—Dualock system of busbar-zone protection; an instantaneous system having dual features for ensuring stability and primarily applicable to new major power-station and large substation switchgear.

(*a*) Operation on straight-through fault. Protection stable because of (i) non-operation of master relay M, (ii) operation of discriminating relay D_4 in lock-out direction L.

(*b*) Operation on internal fault. All oil-circuit breakers tripped by (i) operation of master relay M, (ii) operation of any one discriminating relay D_1, D_2, D_3, or D_4 in tripping-direction T with non-operation of any other in lock-out direction L.

KEY.

D = directional discriminating relay (current-operated).
M = master relay (in balance circuit, set higher than A).
A = alarm relay (set lower than M).
LR = lock-out relay.
TR = tripping relay.
C = main d.c. relay.
P_1 = busbar-zone-fault indicating lamp.
P_2 = alarm-cancelled lamp.
P_3 = instability-alarm lamp.
S = alarm-cancellation switch.

Item D: One per circuit.
Items LR, TR: One per busbar section.
Items M, A, C, P_1, P_2, P_3, S: One per busbar group.

(4) PROTECTIVE SYSTEMS FOR TRANSIENT FAULTS AND EXCESS VOLTAGES IN SUPPLY SYSTEMS INCLUDING OVERHEAD CONDUCTORS

Transient-fault and excess-voltage protection is applied to supply-systems including overhead conductors, and is

intended to protect these and the apparatus associated with them primarily against the effects of lightning, although it usually provides protection also against faults due to other causes, such as birds, twigs, fog, and deposits of dirt and salt, which, for convenience, will be referred to as normal-voltage hazards. Although nearly every supply system includes at least a few overhead lines, there is no need for the whole of it to be provided with transient-fault and excess-voltage protection; it is generally sufficient to protect the overhead lines themselves and the apparatus immediately associated with them.

The effects of lightning surges in an overhead line are twofold; firstly, the effect on the overhead line itself, which may lead to flashover of an insulator and cause a transient fault, requiring transient-fault protection; and secondly, the surges transmitted by the overhead line to station apparatus, which might cause a fault in that apparatus, and therefore require excess-voltage protection. The various methods of dealing with these effects are shown in Fig. 14, reference to which will enable the structure of this section of the paper to be more clearly followed.

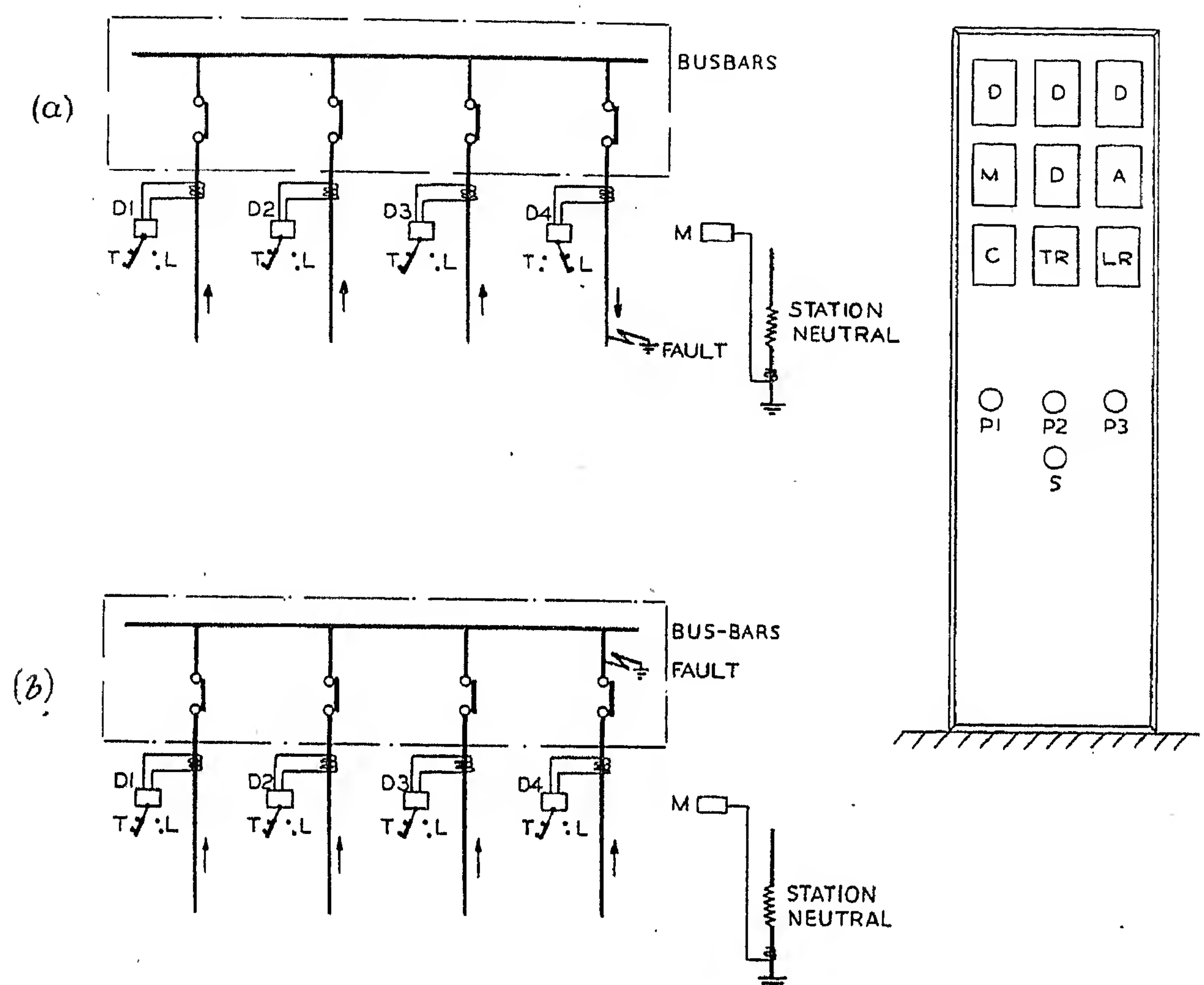


Fig. 13.—Time-lock system of busbar-zone protection: a system primarily applicable to existing major power-station and large substation switchgear.

(*a*) Operation on straight-through fault. Protection stable because of: (i) long time-lag setting of time-lag master relay M, (ii) operation of discriminating relay D_4 in lock-out direction L.

(*b*) Operation on internal fault. Oil circuit-breakers tripped after time-lag because of: (i) operation of time-lag master relay M, (ii) operation of any one discriminating relay D_1, D_2, D_3, or D_4 in tripping direction T and non-operation of any other in lock-out direction L.

KEY.

D = directional discriminating relay (current-operated).
M = time-lag master relay (set higher than A).
A = alarm relay (set lower than M).
LR = lock-out relay.
TR = tripping relay.

C = main d.c. relay.
P_1 = busbar-zone-fault indicating lamp.
P_2 = alarm-cancelled lamp.
P_3 = instability-alarm lamp.
S = alarm-cancellation switch.

Item D: One per circuit.
Items LR, TR: One per busbar section.
Items M, A, C, P_1, P_2, P_3, S: One per busbar group.

(A) Transient-Fault Protection of Overhead Lines

The means for protecting overhead lines against transient faults will now be considered under two headings according to their location.

(a) Means applied to overhead lines.

Means applied to overhead lines are of two kinds, namely those intended to prevent flashover and those intended to prevent an outage after a discharge or a flashover.

(i) *Prevention of flashover by over-insulation, earth wires, and low footing-resistance of towers.*—For the prevention of flashovers it is usual, especially on the lower-voltage

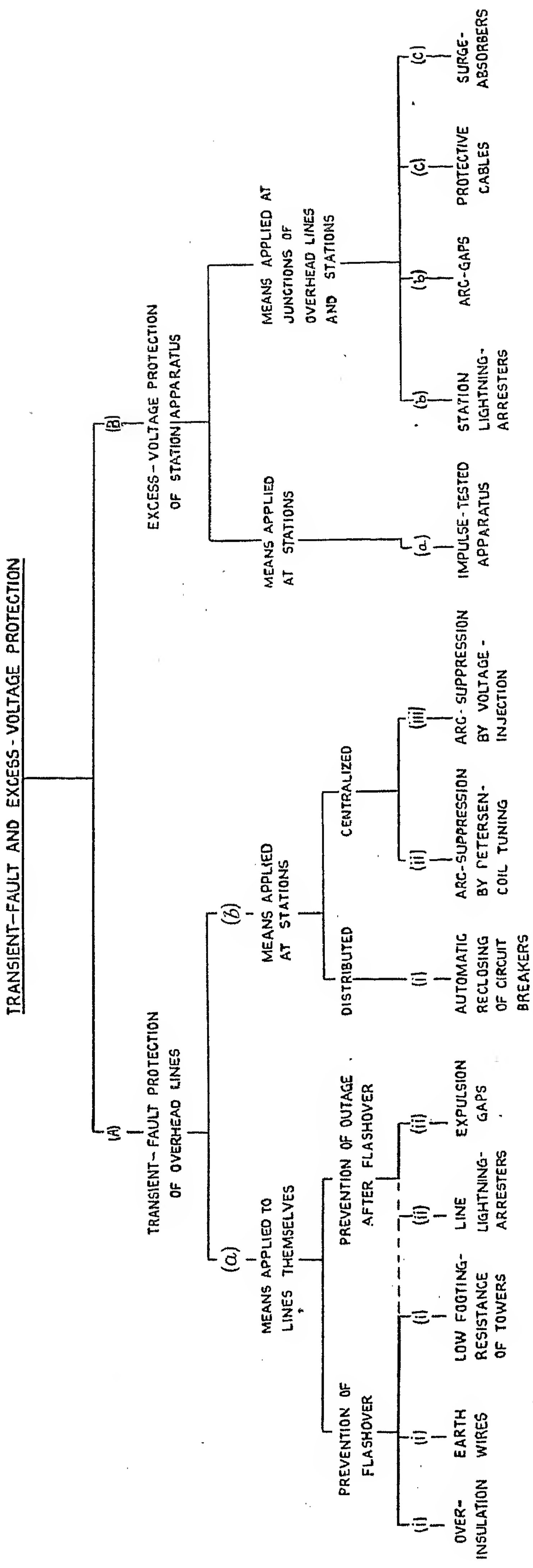


Fig. 14.—Classification of protective systems for transient faults and excess voltages.

The reference numbers and letters refer to corresponding parts of Section (4).

lines, to raise the insulation level above that required for the normal voltage of the system, as laid down, for example, in B.S.S. No. 137, with the object of making the lines less vulnerable to lightning and particularly to normal-voltage hazards. Similarly earth wires arranged to shield line conductors, and low footing-resistances of towers (obtained by using either earth-electrodes of the usual form or relatively long earth-conductors known in the U.S.A. as "counterpoises"), are important in preventing excessive flashover due to lightning only.

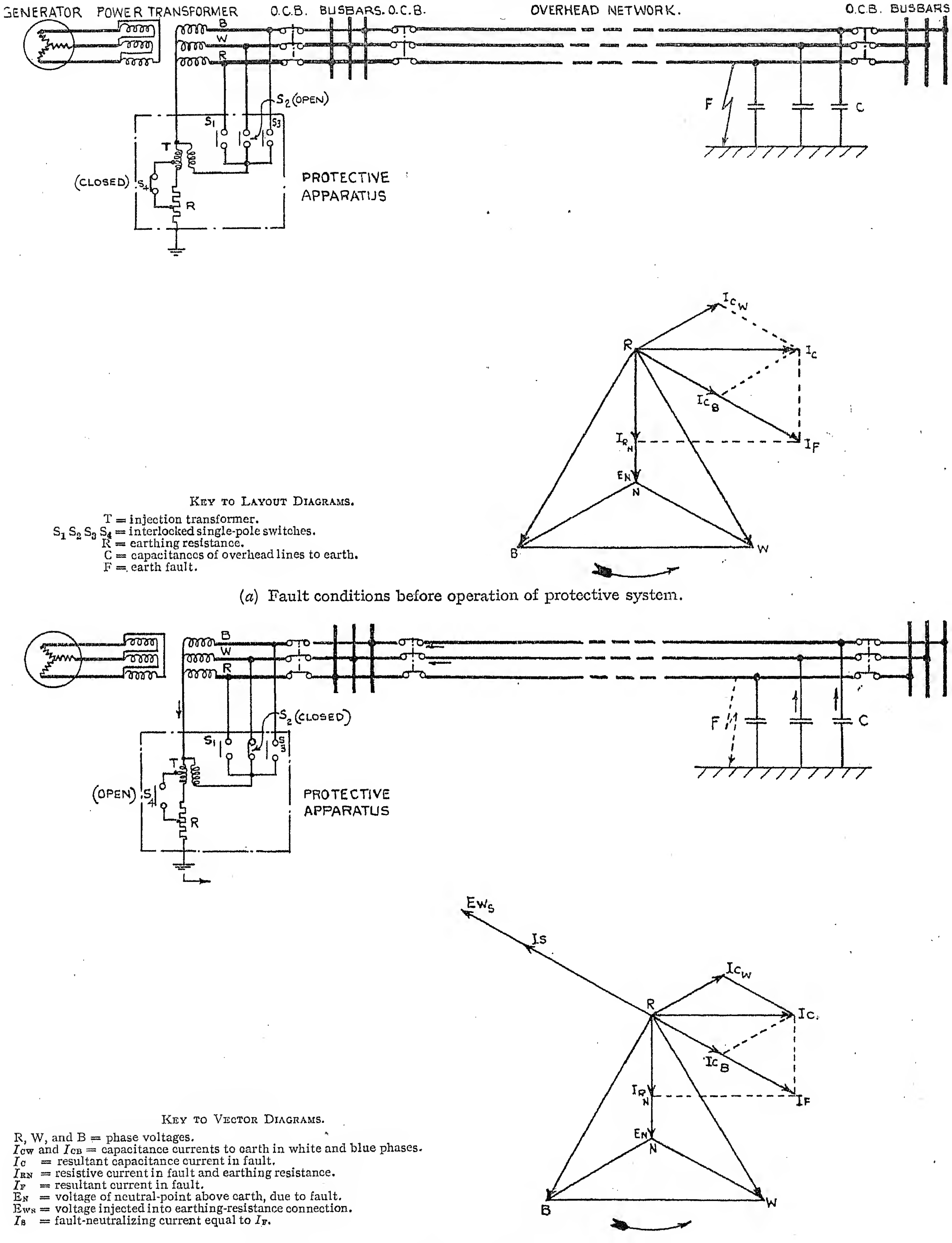
Such means may go a long way towards improving the service efficiency of overhead lines, but it is very doubtful whether they can be applied economically so as to make the lines lightning-proof or completely free from trouble due to normal-voltage hazards. Exceptions are probably very-high-voltage lines so far as some of the normal-voltage hazards are concerned, and lines of, say, 220 kV or more so far as lightning is concerned.

(ii) *Prevention of outage after flashover or discharge by expulsion gaps and line lightning-arresters.*—To allow a flashover to occur for the purpose of discharging lightning effects without a consequent outage, an expulsion gap may be fitted to each line insulator. The device includes a fibre tube fitted in such a way that when a flashover occurs it takes place inside the tube and the arc resulting from the follow-through current is extinguished instantaneously. As an alternative line lightning-arresters may be fitted to a large number of towers. Since both the expulsion gap and the line lightning-arrester function on over-voltage, they protect against lightning only, and not against normal-voltage hazards.

(b) Means applied at stations.

Means applied at stations are of three kinds, namely automatic reclosing of circuit-breakers in the stations associated with the overhead lines to be protected, arc-suppression by Petersen-coil tuning, and arc-suppression by voltage-injection, the two latter being applied to one of a group of stations in the same network.

(i) *Automatic reclosing of circuit-breakers.*—The object of automatic reclosing of circuit-breakers is to isolate a faulty section of overhead line long enough to allow the fault-arc to be extinguished, and then to reconnect the section. The circuit-breakers are tripped automatically if there is a fault on the line, and are reclosed automatically after a predetermined time-lag. The number of possible reclosures usually varies from 1 to 3, and if the fault is transient the affected line is restored to normal service after having been subjected only to a short cessation of supply. This gives adequate protection against transient faults irrespective of whether they are due to lightning or to normal-voltage hazards, and whether one or more phases are affected. Experience shows that as many as 90 per cent of all reclosures are successful, the great majority being first reclosures. The time-interval between tripping and reclosing may be as much as 15 to 30 seconds when temporary disconnection of a line has no adverse effect on the stability of the system. It must, however, be restricted to fractions of a second when it would have a material effect; developments in high-speed reclosing (see Table 5) for this purpose will be dealt with in Section (5).



Key to Layout Diagrams.

T = injection transformer.
S_1 S_2 S_3 S_4 = interlocked single-pole switches.
R = earthing resistance.
C = capacitances of overhead lines to earth.
F = earth fault.

(*a*) Fault conditions before operation of protective system.

Key to Vector Diagrams.

R, W, and B = phase voltages.
I_{CW} and I_{CB} = capacitance currents to earth in white and blue phases.
I_C = resultant capacitance current in fault.
I_{RN} = resistive current in fault and earthing resistance.
I_F = resultant current in fault.
E_N = voltage of neutral-point above earth, due to fault.
E_{WS} = voltage injected into earthing-resistance connection.
I_S = fault-neutralizing current equal to I_F.

(*b*) Fault conditions during operation of protective system.

Fig. 15.—Diagram illustrating transient-fault protective system incorporating arc-suppression by voltage injection.

The fundamental principle of the two arc-suppression schemes about to be described is that the electrical circuit is so arranged or, alternatively, modified during fault conditions, that the current in the fault-arc is suppressed. They can be applied only to systems in which the neutral point may safely be raised to normal phase-potential, and the phases themselves to a potential corresponding to line voltage; and they deal with faults, no matter how they originate, so long as they involve one phase only.

(ii) *Arc-suppression by Petersen-coil tuning*.—The Petersen-coil scheme consists of a choke coil, connected between the neutral point of a supply system and earth, and kept adjusted within prescribed limits so as to form a resonant circuit with the capacitance of the network. The capacitance current through a fault-arc is thus offset by the reactive current through the choke coil, and so the fault current is reduced to such a small value that the arc is extinguished. Thus an earth fault, if transient, is cleared without an outage of the overhead line.

(iii) *Arc-suppression by voltage injection*.—An alternative protective system, at present being tried out, for dealing with transient earth-faults by arc-suppression without resort to a resonant circuit, is illustrated in Fig. 15. This shows both the layout of a section of an overhead-line network protected by this system and the protective apparatus itself, including an injection-transformer T, an earthing resistance R of a value depending upon the capacitance of the network, and single-pole switches S. Although S_1, S_2, S_3, S_4, R, and the primary winding of T are shown connected to the side of the power transformer associated with the protected network, they may for economy be connected to the lower-voltage side without affecting the functioning of the scheme. The conditions in normal service and during the fraction of a second between the occurrence of a fault and the operation of the protective system are indicated in Fig. 15(*a*); and the effect of connecting the centre-point of the injection-transformer T to a similar point of the earthing-resistor R through the circuit-breaker S_4 (which is done as the most effective method of obtaining the required sequence of switching) is to provide an equivalent to the usual resistance-earthing of the neutral point.

The operation of the protective system is shown in Fig. 15(*b*), and the sequence of events is as follows: When a fault occurs on the red phase, as shown, unbalance-voltage relays bring about the closing of the single-pole circuit-breaker S_2 on the white phase (which has the required phase-relationship to the faulty red phase), and this sequentially opens the single-pole circuit-breaker S_4. These operations have the effect of injecting into the neutral circuit a voltage proportional to and in phase with the voltage between the white phase and the neutral point. Since the current I_F in the fault-arc and the current I_S corresponding to the injected voltage would be equal and opposite, as shown in the vector diagrams, the net result is that a negligible current actually flows and the fault-arc is suppressed. After a short time-interval the protective apparatus automatically returns to its normal state, as shown in Fig. 15(*a*). Should the fault happen not to be a transient one, it is then cleared by the ordinary protective gear as described below.

The main differences between the Petersen-coil scheme and the voltage-injection system are that the latter suppresses an arc without a resonant circuit; that it allows greater control over the current in a fault-arc; that the recovery voltage across a fault-arc, which is the difference between the ordinary and the injected voltage, can be maintained at a negligibly small value for a predetermined time, so that the arc does not restrike; and that as a result of improved control there is no need for adjustment of the components of the protective system to match changes in a supply system due to normal switching. In addition, the supply system operates under normal conditions with a resistance-earthed neutral. Thus, although the Petersen-coil scheme may be the simpler of the two, the voltage-injection system appears to offer some advantages.

Arc-suppression schemes are of value in appreciably reducing the number of outages due to transient earth-faults, and are thus beneficial so far as their primary object of clearing such faults is concerned. Should a permanent earth-fault develop, although it is possible to obviate an outage by allowing the supply system to remain in service with one phase earthed and the potential of the neutral raised, the convenience of being able to do so may be offset unless consequent conditions are properly met. For example, unless the insulation of the system is adequate, the increased voltage-stress on the sound phases may weaken their insulation generally. Further, if a second earth-fault develops, it may, in conjunction with the first earth-fault, allow heavy fault currents to damage earth-connections and other apparatus even if it does not cause a widespread shutdown. In addition, broken lines lying on the ground, being only partially earthed, may be dangerous to human and animal life. It is usually possible to overcome these difficulties, but it may be costly to do so, particularly in existing systems. It is frequently better, therefore, to deal with permanent faults by connecting the neutral point to earth automatically, either solidly or through a resistance, as soon as it has been determined by means of a suitable relay that they are permanent, thus causing the ordinary protective gear to disconnect the faulty section in the usual way.

(B) Excess-Voltage Protection of Station Apparatus

To make station apparatus proof against surges entering from overhead lines, its insulation must be suitably co-ordinated with that of the lines, and for this purpose impulse-tested apparatus may be used. Alternatively, a protective device may be interposed at the junction between the line and the station, and this may be a means of effecting economy in insulation of the station apparatus.

(a) Impulse-tested apparatus.

Apparatus rated to withstand a specified impulse-voltage has become known as impulse-tested apparatus. When so rated it is intended to be suitable for connection to overhead lines having a lower impulse-voltage rating,

so that there is a logical co-ordination between its insulation and that of the overhead lines. Since the insulation level of an overhead line is determined by the effects of lightning and normal-voltage hazards, it usually becomes necessary, in order to obtain the required co-ordination, to install station apparatus of a size corresponding to a higher voltage-rating than the actual service voltage. The overall effect is that properly co-ordinated impulse-tested station apparatus becomes uneconomical in comparison with standard station apparatus provided with suitable excess-voltage protective devices.

(b) Station lightning-arresters and arc-gaps.

The feature common to both lightning-arresters and arc-gaps is that they are connected in shunt between each conductor and earth at the junction between the overhead line and the station for the purpose of discharging to earth the lightning surge, thereby relieving the station apparatus of excess voltage entering from the overhead line. When operating they tend to cut off the incoming wave at a voltage corresponding to their setting, without, however, affecting the shape of the wave up to the point of cut-off. This is illustrated in Fig. 16(*a*), which indicates also how high speed of operation increases the effectiveness of the protection by cutting off the impulse wave well before it reaches its crest, which is its most destructive part. Further, its effect on insulation is lessened owing to its reduced duration, and the inter-turn stresses produced by it are confined chiefly to the end windings of a transformer. In general, it may be said that the operating speed of a gap is higher the more closely it approaches a sphere-gap, and that the operation of a rod-gap or a point-gap is relatively slow. An arc-gap suitable for the excess-voltage protection of station apparatus should necessarily be of the high-speed type. Although good arc-extinguishing properties are desirable, they must not be obtained at the expense of operating speed.

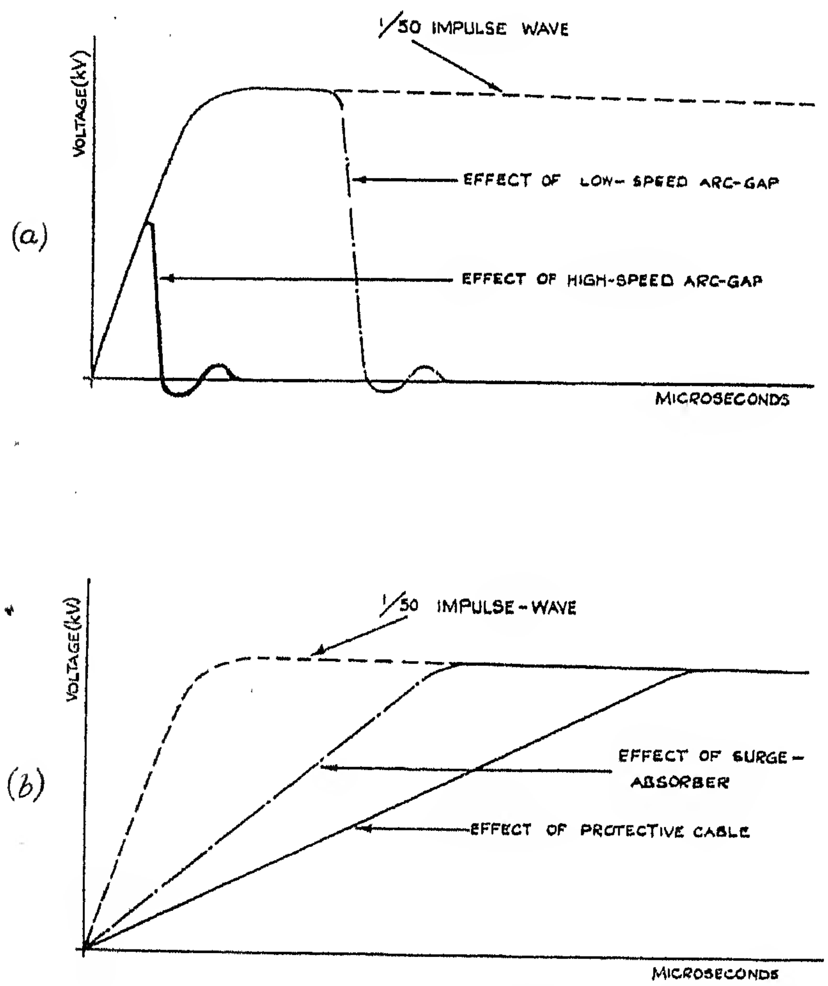


Fig. 16.—Diagram illustrating effects of various protective devices on a typical impulse wave.

(*a*) Arc-gaps.
(*b*) Series protective devices.

Of the many types of lightning arrester available, the most effective appears to be one that includes an arc-gap in series with a material having a high resistance at normal line-voltage and a decreasing resistance at higher voltages, so that the lightning arrester shunts considerable currents to earth at lightning voltages but the power arc does not persist. An alternative, also dealing effectively with power follow-through current, is to use a high-speed arc-gap in combination with an arc-suppression scheme or with automatic reclosing of circuit-breakers. As compared with lightning arresters this has the important advantages of lower first cost, higher speed of operation, and higher discharge-capacity owing to the absence of any limiting series resistance.

(c) Protective cables and surge absorbers.

A protective cable is a cable a few hundred yards long connected between an overhead line and station apparatus. A surge absorber usually consists of an inductance coil of high capacitance to earth connected in series with a line.

As distinct from lightning arresters and arc-gaps, which are shunt devices, both protective cables and surge-absorbers are series-connected. Their mode of operation is therefore different in that fundamentally they reduce not the amplitude of an impulse wave but only its steepness. This is illustrated in Fig. 16(*b*). The reduction in steepness may have the additional effect that the wave, particularly if it is short, does not reach its full amplitude.

If protective cables are reasonably long (their minimum length depending upon the degree to which a line is over-insulated in relation to station apparatus), they form a beneficial safeguard for the insulation of station apparatus, particularly transformers. The additional expense they involve has often to be incurred in any event for reasons of public safety, owing to the proximity of substations to dwellings.

(C) General Discussion of Transient-Fault and Excess-Voltage Protection

After the foregoing brief description of the various protective means available, a summary of the considerations governing their application may be appropriate. This can only be stated in general terms, since in practice many local considerations have an important bearing on the problem and have to be taken into account.

(a) Overhead lines.

In relation to the protection of overhead lines against transient faults, the most important points are, first, the cause of the flashover, namely whether it is due to lightning or to the normal-voltage hazards of birds, twigs, and

deposits from any cause; and, second, the nature of the flashover, namely whether it involves only one phase or more than one phase. Obviously, if the majority of faults are caused by normal-voltage hazards, protective devices that deal with lightning only are of little value; and, similarly, in the unlikely event of a preponderance of phase faults, protective systems that deal with earth faults only would not greatly improve service efficiency.

It is advisable to prevent flashover as far as possible by over-insulating lines, by providing earth wires, and by ensuring low footing-resistances of towers; but there are economical limits beyond which it is not desirable to go, and the provision of further means for preventing flashover must be considered.

Broadly speaking, transient faults on lower-voltage lines, say from 6·6 kV to 33 kV, are due both to lightning and to normal-voltage hazards, and, assuming reasonably low footing-resistances of towers, the great majority of faults are earth faults. These considerations narrow down the choice of protective means for preventing outages by dealing with transient faults on the lower-voltage lines either to automatic reclosing of circuit breakers or to arc-suppression systems. Although automatic reclosing of circuit-breakers can deal with both earth faults and phase faults, arc-suppression schemes, in spite of their dealing only with earth faults, are often to be preferred on account of lower first cost, centralization, and reduced maintenance.

At the other end of the range, transient faults on overhead lines above 100 kV are almost entirely due to lightning, and the majority are earth faults. Two additional factors have to be taken into account: the first is that appreciable saving is possible by grading the insulation of power transformers towards the neutral points and by earthing the neutral points solidly, which precludes the use of arc-suppression schemes; and the second is that in view of the comparatively small number of circuit-breakers required for controlling large amounts of power it is economical to make them suitable for automatic reclosing. Thus for lines above 100 kV automatic reclosing of circuit-breakers compares favourably with arc-suppression schemes and is to be preferred. The remaining alternatives, namely expulsion gaps and line lightning-arresters, do not as a rule compare favourably with reclosing of circuit-breakers on account of their necessarily large number and hence high first cost, and the increased numbers of components that have to be maintained.

(b) Station apparatus.

Three possible methods of protecting station apparatus may be briefly referred to. The first is to use impulse-tested apparatus. The second is to use ordinary apparatus in conjunction with protective cables or surge absorbers to reduce the steepness of impulse waves and high-speed arc-gaps to cut off their crests, in association with an arc-suppression scheme or automatic reclosing of circuit breakers. The third is the same as the second, except that lightning arresters are substituted for the high-speed arc-gaps and the arc-suppression scheme or reclosing circuit-breakers. Although these are all suitable technically, they may often have to be ruled out on economic grounds, and then the problem is to find the most satisfactory alternative. As a good all-round solution the authors suggest the use of high-speed arc-gaps for protecting station apparatus against excess voltages, in association with an arc-suppression system or with automatic reclosing circuit-breakers (either of which may already have been provided for the transient-fault protection of overhead lines), which clear the fault-arcs in the high-speed arc-gaps as transient faults. Alternatively, and particularly when transient-fault protection is not available, lightning arresters may be used. High-speed arc-gaps may also be used alone, but they usually entail some increase in the number of outages.

(c) Summary.

It would appear that the best compromise between the technical and economic considerations governing both the transient-fault protection of lines and the excess-voltage protection of station apparatus is secured as follows:—

Transient-fault protection is obtainable for lower-voltage lines, say from 6·6 kV to 33 kV, by using one of the two arc-suppression schemes; for higher-voltage lines, say above 100 kV, by means of automatic reclosing of circuit-breakers; and for lines of intermediate voltage by either method. This is additional to the fundamental safeguards of adequate insulation, earth wires, and low footing-resistances of towers.

Excess-voltage protection of station apparatus is obtainable by means of high-speed arc-gaps operating in conjunction with transient-fault protection of the lines. This allows standard station apparatus to be used, and obviates the use of the more expensive impulse-tested apparatus and of long runs of cable.

(5) CIRCUIT-BREAKERS FOR FAULT CLEARANCE

The quest for increased speed of fault clearance has meant increasing the speed of protective safeguards, which include not only protective systems such as those described in Sections (3) and (4) but also circuit-breakers. For ease in distinction, it is proposed to refer to circuit breakers having total-break times from the closing of the trip-coil circuit to the instant of final arc-extinction in all poles of 5 cycles or less throughout their whole breaking-capacity range as "high-speed," and to those having longer total-break times up to 15 cycles on the same basis as "fast-acting." The present position, stated generally, is that the use of fast-acting circuit-breakers, fully proved at short-circuit testing stations, is established practice, and that some high-speed circuit-breakers, having already progressed beyond their development stage, are emerging into service.

(A) Examples of Clearance Times with Fast-acting Circuit-Breakers

As a guide to the total time required to clear a fault, Table 2 gives results obtained with fast-acting metalclad switchgear and protective systems suitable for three types of duty in a supply system. All the circuit-breakers are fitted with solenoid operation and electromagnetic tripping-devices. Distribution switchgear is typified by an 11-kV oil circuit-breaker rated at 150 MVA and operating in conjunction with a balance protective-system; power-station switchgear by a 33-kV oil circuit-breaker rated at 1 500 MVA and operating in conjunction with a balance

Table 2

EXAMPLES OF REPRESENTATIVE FAULT-CLEARANCE TIMES WITH SOLENOID-OPERATED METAL-CLAD SWITCHGEAR WORKING IN CONJUNCTION WITH INSTANTANEOUS AUTOMATIC PROTECTIVE SYSTEMS

(A) *With 11-kV Distribution Switchgear*

Three-phase solenoid-operated oil circuit-breaker fitted with plain-break contacts and electromagnetic tripping.

Breaking-capacity rating at 11 kV: Symmetrical, 7 800 r.m.s. amperes (equivalent to 150 MVA); Asymmetrical, 9 750 r.m.s. amperes.

Automatic protection: Solkor system (balance class).

Function	At 10 to 15 per cent of rating		At 100 per cent of rating	
	Cycles	Seconds	Cycles	Seconds
(i) Opening time	4·0	0·08	4·0	0·08
(ii) Arc duration	3·5	0·07	2·0	0·04
(iii) Total-break time: (i) plus (ii)	7·5	0·15	6·0	0·12
(iv) Relay-operating time	6·0	0·12	4·0	0·08
(v) Fault-clearance time: (iii) plus (iv)	13·5	0·27	10·0	0·20

(B) *With 33-kV Power-Station Switchgear*

Three-phase solenoid-operated oil circuit-breaker fitted with vertical turbulators and electromagnetic tripping.

Breaking-capacity rating at 33-kV: Symmetrical, 26 000 r.m.s. amperes (equivalent to 1 500 MVA); Asymmetrical, 32 500 r.m.s. amperes.

Automatic protection: Split-pilot system (balance class).

Function	At 10 to 15 per cent of rating		At 100 per cen tof rating	
	Cycles	Seconds	Cycles	Seconds
(i) Opening time	6·5	0·13	6·5	0·13
(ii) Arc duration	3·0	0·06	1·5	0·03
(iii) Total-break time: (i) plus (ii)	9·5	0·19	8·0	0·16
(iv) Relay-operating time	3·0	0·06	3·0	0·06
(v) Fault-clearance time: (iii) plus (iv)	12·5	0·25	11·0	0·22

(C) *With 132-kV Transmission Switchgear*

Three-phase solenoid-operated oil circuit-breaker fitted with horizontal turbulators and rotary moving contacts and electromagnetic tripping.

Breaking-capacity rating at 132 kV: Symmetrical, 6 600 r.m.s. amperes (equivalent to 1 500 MVA); Asymmetrical, 8 250 r.m.s. amperes.

Automatic protection: High-speed Ratio-balance system (distance class).

Function	At 10 to 15 per cent of rating		At 100 per cent of rating	
	Cycles	Seconds	Cycles	Seconds
(i) Opening time	3·0	0·06	3·0	0·06
(ii) Arc duration	3·0	0·06	1·5	0·03
(iii) Total-break time: (i) plus (ii)	6·0	0·12	4·5	0·09
(iv) Relay-operating time	4·0*	0·08	2·0*	0·04
(v) Fault-clearance time: (iii) plus (iv)	10·0	0·2	6·5	0·13

* Throughout the instantaneous zone; for other times see Fig. 8.

protective-system; and transmission switchgear by a 132-kV oil circuit-breaker rated at 1 500 MVA and operating in conjunction with a distance protective-system. For convenient reference, the operating time of a protective system and the total-break time of a circuit breaker are stated in terms of 50-cycles-per-second cycles as well as in seconds. Thus, in Example A of Table 2 the total-break time at 100 per cent of the breaking-capacity rating is 6 cycles, and the corresponding protective-system operating time is 4 cycles, so that the fault-clearance time is 10 cycles (0·20 second). Table 2 indicates the extent to which speed of fault clearance depends upon the mechanical opening-time of the circuit-breaker. Example C records data of a 132-kV 1 500-MVA circuit-breaker with solenoid closing and electromagnetic tripping fitted, on the lines of Fig. 17, with horizontal turbulators, and with rotary moving contacts in order to reduce the inertia of its moving parts compared with that of the usual arrangement of vertical-moving contacts. This construction not only reduces the oil in the tank by 40 per cent but also reduces the total break time at 100 per cent breaking-capacity to 4·5 cycles, thus putting the circuit-breaker into the high-speed category at that rating, although over the whole range, it must be classified as fast-acting. This and other experience pointed to the possibility of effecting further improvements in the directions of reduction of oil volume and increased speed of fault clearance by suitable rearrangement of known types of circuit-breaker components.

(B) High-Speed Circuit-Breakers

High-speed circuit-breakers, as compared with fast-acting, are particularly advantageous for high-voltage transmission lines interconnecting large generating-centres, because they enable faults to be isolated so rapidly that stability of the interconnected supply systems is not endangered. They are also an essential component in providing a means of restoring supply with minimum disturbance by rapid reclosure on transient faults; this matter will be dealt with below. Of the many considerations that arise in the practical development of a high-speed circuit-breaker, two fundamental problems may be mentioned. The first is the mechanical problem of rapid acceleration and high speed of travel of the moving parts and arcing contacts to produce the necessary break within the required time of a cycle or so, and their subsequent rapid retardation; and the second is the electrical problem of the rapid control of de-ionization of the arc path in the break to produce high-speed arc extinction.

The turbulator arc-control device having been developed by tests with an experimental circuit-breaker (capable of very high speed of break), and having proved to be reliable for breaking circuit with arc-durations of 1 cycle or less as well as for making circuit, the development of high-speed circuit-breakers resolved itself chiefly into a solution of the mechanical problem. To bring the 132-kV circuit-breaker of Example C of Table 2 into the high-speed class, its solenoid closing and electro-

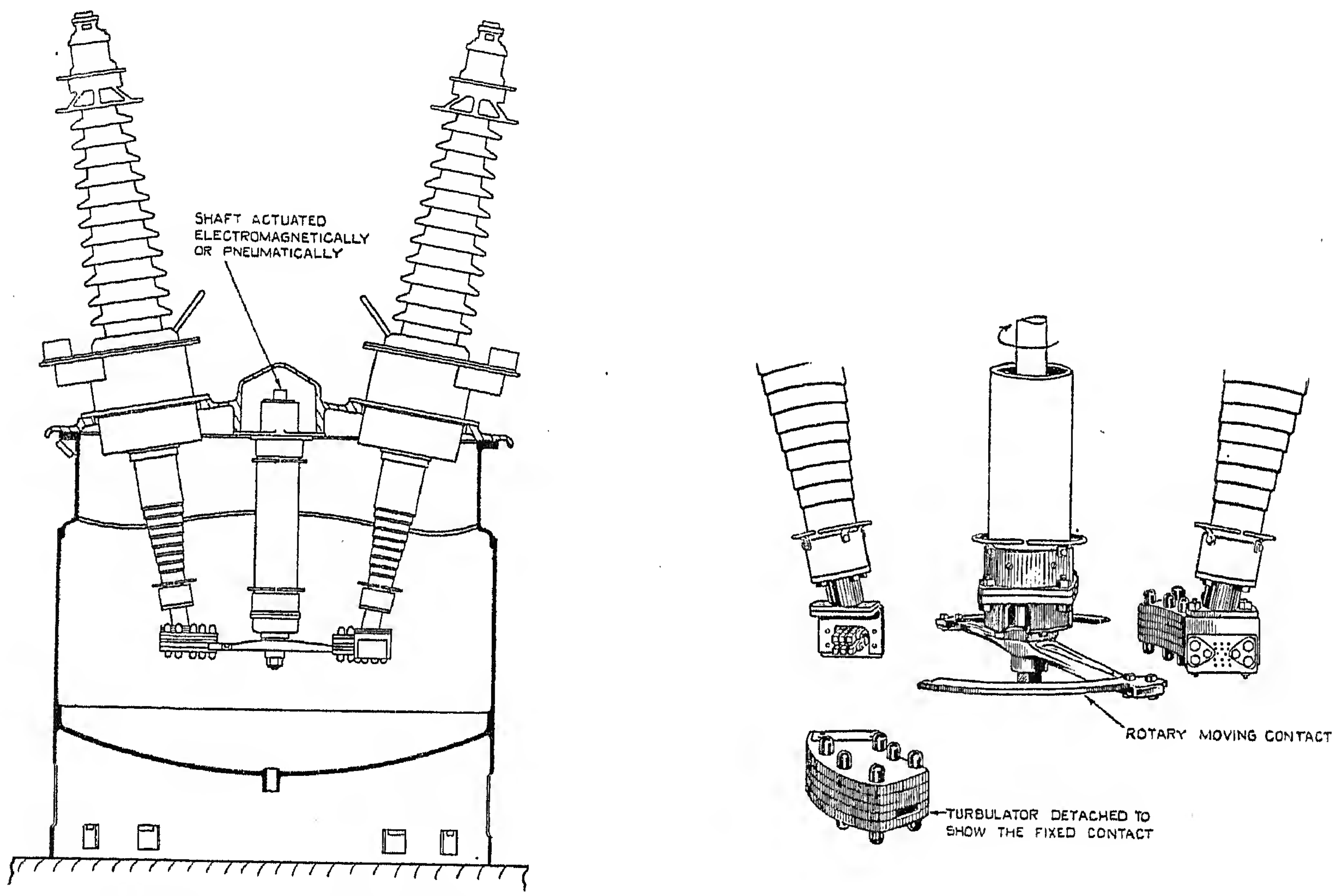


Fig. 17.—Assembly and isometric diagram of a single-phase unit of a 1 500-MVA 132-kV 3-phase oil circuit-breaker fitted with horizontal turbulators and rotary moving contacts.

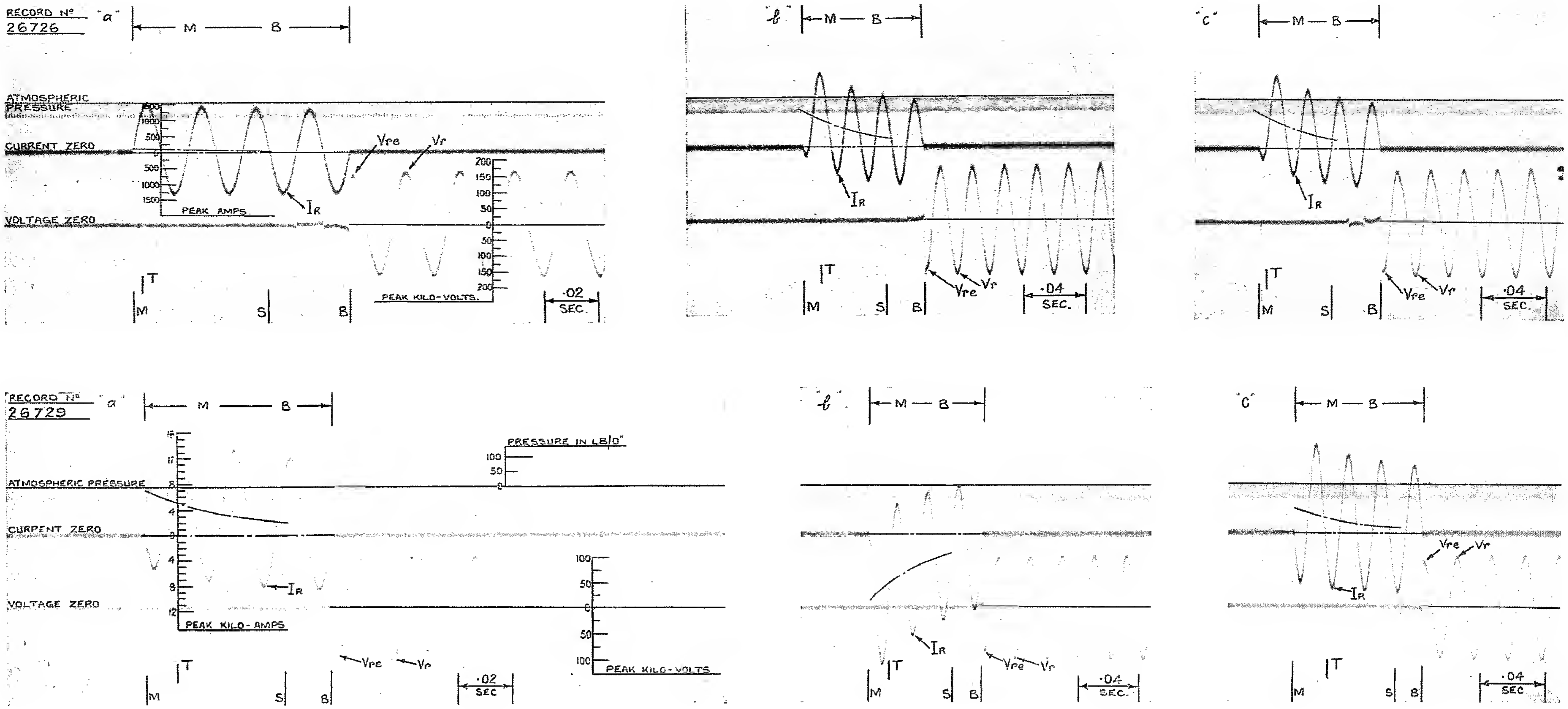


Fig. 18.—Oscillograms of short-circuit tests of the 1 500-MVA 132-kV pneumatically-operated circuit-breaker referred to in Tables 3 and 4.

M = instant of application of short-circuit.
T = instant of closing trip-coil circuit (obtained from a complementary oscillogram).
S = instant of separation of arcing contacts.
B = instant of arc extinction.

Time interval T to B :— total break time.
,, ,, T to S :— opening time.
,, ,, S to B :— arc duration.

magnetic tripping devices were discarded in favour of faster pneumatic power closing and opening. The improved performance obtained is given in Fig. 18 (see Plate, facing page 468) and Tables 3 and 4, from which it will be seen in comparison with Example C of Table 2 that the total break-time is 4 cycles maximum instead of 6, and 3 instead of 4·5 at 100 per cent rating; and the arc duration is 1·5 cycles maximum, and 1 cycle at 100 per cent rating.

To reduce the amount of oil required and to achieve a still higher speed of operation, a turbulator circuit-breaker of the small-oil-volume single-break type indicated in Figs. 4A and 4B has been developed. It is closed and opened by what may be called "pneumo-oil" opera-

Table 3

EXAMPLE OF HIGH-SPEED CIRCUIT-BREAKING AND SHORT FAULT-CLEARANCE TIMES WITH THE 1 500-MVA 132-KV PNEUMATICALLY-OPERATED CIRCUIT-BREAKER OF FIG. 17 WORKING IN CONJUNCTION WITH HIGH-SPEED DISTANCE PROTECTION

Three-phase pneumatically-operated high-speed circuit-breaker fitted with horizontal turbulators and rotary moving contacts.

Breaking-capacity rating at 132 kV: Symmetrical, 6 600 r.m.s. amperes (equivalent to 1 500 MVA); Asymmetrical, 8 250 r.m.s. amperes.

Automatic protection: High-speed ratio-balance system (distance class).

Function	At 10 to 15 per cent of rating		At 100 per cent of rating	
	Cycles	Seconds	Cycles	Seconds
(i) Opening time	2·5	0·05	2·0	0·04
(ii) Arc duration	1·5	0·03	1·0	0·02
(iii) Total-break time: (i) plus (ii)	4·0	0·08	3·0	0·06
(iv) Relay-operating time	4·0*	0·08	2·0*	0·04
(v) Fault-clearance time: (iii) plus (iv)	8·0	0·16	5·0	0·1

* Throughout the instantaneous zone; for other times see Fig. 8.

Table 4

SHORT-CIRCUIT PERFORMANCE VALUES OF THE 1 500-MVA 132-KV PNEUMATICALLY-OPERATED CIRCUIT-BREAKER OF FIG. 17 (SEE ALSO TABLE 3 AND FIG. 18)

Single-phase performance at 50 cycles per second

Test record number	Duty cycle	Applied voltage (kV)	Breaking current: R.M.S. values: A.C. component only: Amperes	Breaking current: R.M.S. values: A.C. component only: Percentage of rating	Breaking current: R.M.S. values: A.C. and D.C. components (amperes)	Breaking current: D.C. component (percentage of a.c. peak current)	Recovery voltage (kV)	Total break-time: Seconds	Total break-time: Cycles	Arc-duration (cycles)	Behaviour
26726	B	125	950	14	950	0	113	0·082	4·1	1·5	Peaceful
	3 B	125	930		970	15·3	117	0·070	3·5	1·3	Peaceful
	3 B	125	930		990	21·4	116	0·076	3·8	1·5	Peaceful
26729	B	76	7 150	110	7 420	19·8	69·7	0·058	2·9	0·9	Peaceful
	3 B	76	7 150		7 760	29·7	68·6	0·062	3·1	1·0	Peaceful
	3 B	76	7 070		7 140	10	69·6	0·062	3·1	0·8	Peaceful

tion, and the principle of its mechanical operation is illustrated in Fig. 19. It will be seen that the inertia of the moving parts has been reduced to merely that of the to this relatively light moving contact-rod and of arresting its motion. A sufficient number of tests have been made to demonstrate the possibility of high-speed opera-

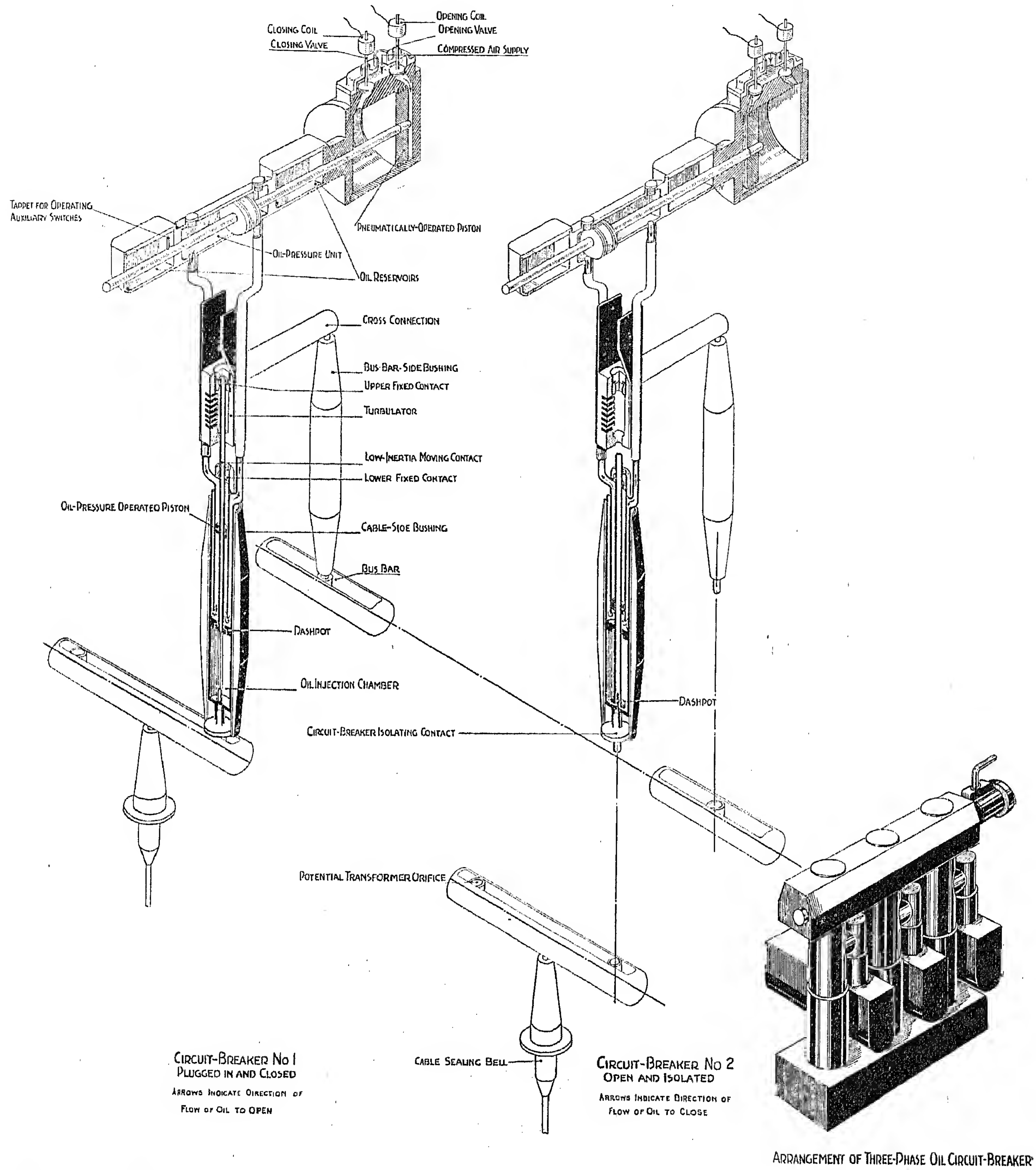


Fig. 19.—Isometric diagram illustrating in principle the pneumo-oil operation of the low-inertia moving-contact members of high-speed circuit-breakers of the type illustrated in Figs. 4A and 4B.

metal rod contact required to bridge the break between the fixed contacts, and that the pneumo-oil mechanism uses oil as a means of transmitting the accelerating forces tion and fault clearance with an arc duration of the order of 1 to 1·5 cycles throughout the whole breaking-capacity range.

(C) Automatic Reclosing of Circuit-Breakers

The use of automatically-reclosing high-speed circuit-breakers to protect overhead lines against the transient faults referred to in Section (4) applies particularly to high-voltage single-tie lines transmitting large amounts of power between two areas of supply containing synchronous machinery.

Two requirements govern the time of reclosure: on the one hand it should be so short that synchronous machinery is not in danger of falling out of step; but on the other hand it should be long enough to allow the fault-arc to extinguish itself completely, so that it does not restrike when the circuit-breaker is reclosed. Both times are variable, the former depending upon the characteristics of the synchronous plant and of the tie line as well as upon the severity of a fault preceding reclosure, and the latter upon the amount of ionized air generated during a fault, i.e. upon duration of fault, arc length, system voltage, fault current, and atmospheric conditions. The present state of knowledge is not sufficient to provide definite data for all voltages and conditions of supply, but as a guide it is possible to refer to American field-test experience* on a 132-kV 60-cycle system, from which it appears that successful reclosures can be obtained without loss of synchronism if the total time between the beginning of a

Table 5

An Example of Automatic Reclosing with the High-Speed 1 500-MVA 132-kV Pneumatically-Operated Circuit-Breaker of Fig. 17 Working in Conjunction with High-Speed Distance Protection (see also Table 3)

Three-phase pneumatically-operated oil circuit-breaker fitted with horizontal turbulators and rotary moving contacts.

Breaking-capacity rating at 132 kV: Symmetrical, 6 600 r.m.s. amperes (equivalent to 1 500 MVA); Asymmetrical, 8 250 r.m.s. amperes.

Automatic protection: High-speed ratio-balance system (distance class) and reclosing relays.

(A) *Performance of Circuit-Breaker without Protective System*

Function	At 100 per cent of rating	
	Cycles	Seconds
(i) Total-break time	3·0	0·06
(ii) Time from arc-extinction to breaker fully open	2·5	0·05
(iii) Total time from closing of trip-coil circuit to circuit-breaker fully open: (i) plus (ii)	5·5	0·11
(iv) Time from initiation of reclosing to contact-make	5·0	0·1
(v) Time from contact-make to circuit-breaker fully home	0·5	0·01
(vi) Total time from closing of trip-coil circuit to circuit-breaker fully home: (iii) plus (iv) plus (v)	11·0	0·22

(B) *Combined Performance of Protective System and Circuit-Breaker, Illustrating Effect on Tie Line*

Function	At 100 per cent of rating	
	Cycles	Seconds
(i) Relay-operating time	2·0*	0·04
(ii) Total break time of circuit-breaker	3·0	0·06
(iii) Fault-clearance time: (i) plus (ii)	5·0	0·10
(iv) Time during which tie line is completely de-energized: A (ii) plus A (iv)	7·5	0·15
(v) Total time from incidence of fault to contact-make: (iii) plus (iv)	12·5	0·25
(vi) Total time from incidence of fault to circuit-breaker fully home: A (v) plus (v)	13·0	0·26

* Throughout the instantaneous zone; for other times see Fig. 8.

* P. Sporn and D. C. Prince: *Electrical Engineering*, 1937, vol. 56, p. 81.

fault and the reclosing of the circuit is not more than 20 cycles, and without risk of restriking the fault-arc if the time during which the tie line is completely de-energized is not less than 12 cycles. These values correspond to 17 and 10 cycles respectively at 50 cycles per second.

Although these limits would allow the use of a fast-acting circuit-breaker with a fault-clearance time up to 7 cycles, it is very desirable for the sake of reliability to reduce this time to a minimum by the use of a high-speed circuit-breaker. There are two reasons for this: the first is to reduce as much as possible the amount of ionized gas produced by the transient fault, and so to minimize the time during which the line must be de-energized; and the second, which depends upon the first, is to restore supply by reclosure as quickly as possible within the limit of 17 cycles. Further, the shorter the total time or de-energization is, the greater may be the power transmitted over the tie line without risk to synchronous plant.

The performance of the pneumatically-operated 132-kV high-speed circuit-breaker of Fig. 17 when used for automatic reclosing is shown as an example in Table 5A, and the corresponding schedule of times, including operation of the protective system and effect on the tie line, is shown in Table 5B. This indicates that the circuit-breaker can clear the fault and re-energize the line in 12·5 cycles, and reclose right home in a total time of 13 cycles. It remains to consider how its operating times compare with the service requirements stated above. The fault would be cleared in 5 cycles, compared with the 7 cycles allowable; to comply with the 10 cycles required for de-energization of the line, the reclosing would have to be delayed from 7·5 cycles to 10 cycles; and the line would then be re-energized after clearing a transient fault in 15 cycles compared with the 17 cycles allowable.

The pneumo-oil-operated circuit-breaker of Figs. 4A and 4B is particularly suitable for automatic high-speed reclosing service at high voltages. High-speed reclosing of circuit breakers, by de-energizing the transmission line only momentarily, can form an important safeguard against interruption of supply.

(6) CONCLUSION

As a result of studying past experience in the preservation of continuity of electricity supply from the point of view of modern conditions and tendencies and the improved safeguards now available, the authors offer the following as items for discussion.

(1) The ever-increasing dependence of the public and industry upon electricity, and their increasing consumption of it over extended interconnected areas, have brought about more exacting demands for an uninterrupted supply. In consequence, safeguards against interruption, without which neither economy nor continuity is possible, have become of even greater importance, and have been developed accordingly.

(2) The interruptions of supply experienced in the past have usually been traceable to faults in components inadequately safeguarded, resulting in sustained arcing against which the ultimate safeguard of fire-fighting equipment is of little avail. Such liberation of uncontrolled energy is in itself a powerful source of intense fire, which inevitably does damage of an amount depending upon the time for which it persists. Economical freedom from such liability is best ensured by rapid isolation of faulty apparatus.

(3) If it is thought to be detrimental to have such interruptions of supply as have occurred in the past, and if the risk of their recurrence is regarded as an uneconomic liability for the future, appropriate general, routine, and protective safeguards should be adopted in order to prevent them, with ultimate safeguards as a final stand-by.

(4) When the available safeguards are put into a proper perspective of technical and economic utility, it becomes clear that general and routine safeguards cope with the risk of the occurrence of faults, that protective safeguards deal with faults themselves by isolating them rapidly when they occur, and that ultimate safeguards, although they may shorten interruptions of supply, are generally of little, if any, value as a means of preventing them, since they deal with outages only in their serious stages.

(5) Adoption of general safeguards involves careful design of a supply network, which should be so planned that the most efficient and economical use is made of all its test-proved components under both load and short-circuit conditions. As far as practicable, the layout of the system should permit the rapid isolation of a faulty component to occur as an outage that does not necessarily involve an interruption of supply.

(6) Amongst routine safeguards, power-factor testing on site may have its uses; but it can never take the place of the vital safeguard of high-quality insulation tested stage by stage during manufacture.

(7) Protective safeguards provide the all-important means of ridding a supply system from a faulty component by isolating it as an outage before the fault has time to do serious damage. The advent of high-speed protective systems and circuit-breakers brings with it even greater effectiveness in fault clearance than has been afforded already by instantaneous protective systems and fast-acting circuit breakers.

(8) Busbar-zone protection has not hitherto been usually included in supply systems, but if it is thought that the risk of major damage and interruption of supply ought to be still more rigidly minimized this form of protection should be more generally applied.

(9) The avoidance of unnecessary outages of overhead lines by transient-fault protection, and of unnecessary damage of associated station apparatus by excess-voltage protection, is a further aid to maintenance of continuity of supply.

(10) Automatic protective safeguards suitably applied are an invaluable aid to the control engineer during times of disturbance of a supply system, since they free him from undue responsibility and enable him to attend to other duties associated with restoration of supply.

(11) Ultimate safeguards may be regarded as a final means of minimizing damage by fire or otherwise and of dealing with hazards outside the control of the electrical industry.

(7) ACKNOWLEDGMENTS

The authors wish to express their indebtedness and thanks to Messrs. A. Reyrolle and Co., including Mr. F.

Coates and Mr. H. W. Miller, directors of the Company; to Mr. L. E. Mold and Mr. C. A. Stephens for many useful suggestions; and to Mr. T. Carter, Mr. J. Mirrey, Mr. A. Allan, Mr. J. A. Harle, Mr. D. E. Lambert, Mr. I. W. A. Kirkwood, and others who have assisted in the preparation of the paper.

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DISCUSSION BEFORE THE INSTITUTION, 6TH JANUARY, 1938

Mr. Johnstone Wright: In Table 1 the maximum permissible short-circuit MVA is given as 500 at 6·6 kV and 750 at 11 kV. If systems cannot be handled at these voltages without exceeding these MVA values, then in my opinion consideration should be given to the use of a higher voltage of transmission.

The switchgear layout shown in Fig. 3 is novel and attractive, in that it makes provision for inspection of all the component parts, including the busbars, but in order to give this facility it has been necessary to introduce numerous isolators and thus weaken the busbars. Busbar protection is therefore more necessary in this than in the normal layout. The arrangement shown in Fig. 3 is unfortunately not a cheap one.

I am not entirely in agreement with the authors' conclusions regarding ultimate safeguards (page 454). My experience shows that it is inadvisable to save on the cost of the ultimate protection in order to spend more on the protective gear. I think we should provide adequate sectionalizing arrangements, with, if necessary, automatic fire-fighting equipment. Although we know that sometimes the reason for the supply failing is the protective gear, it is encouraging to recall that during 1937 the proportion of correct operations of protective gear on the grid system was 86 per cent. We hope that in time the figure will be 96 per cent, but to achieve this will mean careful manufacture and equally careful maintenance by the supply authorities. On the big supply systems in America the percentage of correct operations on the protective gear is just as high as in this country, and American engineers are making every effort to raise their figure to as near 100 per cent as possible.

The authors stress the importance of busbar protection, and refer to the greater use made of it in the United States and on the Continent than in this country. But engineers, even in these places, are not yet wholly satisfied that busbar protection is worth while. I firmly believe that in time busbar protection will become standard practice, but before we adopt it extensively we should be sure that we are not introducing a hazard greater than the one we are trying to provide against. In this country the main-busbar failures have not been very many compared with the number of main busbars in operation. We should also bear in mind that there are certain physical arrangements of switchboards in which sections of busbar are included with the circuit protection and do not require special protection.

I am interested in the authors' alternative to the Petersen arc-suppression coil for giving protection against transient faults on overhead lines; unfortunately its sensitiveness depends to a certain extent on the distance of the fault from the earthing point. I should be interested to know how far the authors' experiments with this device have gone.

I should be glad to have more particulars of the construction and action of the single-break circuit-breaker. From the description given in the paper it seems to me that the oil required for operation is kept quite separate from the oil for extinction; but I should like to have the authors' confirmation of this. If this is not the case, the circuit-breaker seems to be based on the same principle as the "impulse" breaker which has been developed in the United States in connection with the Boulder Dam scheme, and recently in this country. The first installation of that make of switchgear manufactured in this country is being installed at one of the C.E.B.'s substations.

Auto-reclosing of switches has proved invaluable in America on systems operating at voltages up to 33 kV, and I am sure that in time it will be more and more used on overhead lines. The C.E.B. have tried it out in a small way.

Mr. T. W. Ross: It is unfortunate that the authors do not describe in greater detail the safeguards dealt with in the paper: for instance, the only relay described is the high-speed directional relay (page 455). This is based on a principle which, I believe, is not entirely suitable for the conditions met with in practice, and I prefer to employ directional relays which are fundamentally true wattmeters. It seems doubtful whether the authors' relay will operate successfully on heavy current and low voltage, because the flux due to the current winding may then be so much in excess of that due to the voltage winding that the latter would be insufficient to provide the unbalance necessary to operate the relay. Some further information on this point would be of interest.

High-speed directional relays based on the induction-wattmeter principle, having an operating time of less than 1 cycle, are in successful use in this country, and it has not been found necessary to introduce artificial delay

to overcome transient phase-displacement. Perhaps the authors could state why they consider a delay of 1 to $1\frac{1}{2}$ cycles is necessary in the case of their relay when such delay is not necessary for wattmeter-type relays. I would also like to know by what means the delay is obtained.

The Interlock protective system described on page 457 apparently depends upon time as a stabilizing factor, but I consider that some arrangement for controlling the sequential operation of the relays and locking signals is preferable, particularly when such small intervals of time are employed.

The chief difficulty with busbar-zone protection is to design a system which is reasonably simple, selective, and completely stable during all conditions met with in practice. The problem becomes much more difficult when multiple-busbar systems are under consideration, particularly when safety interlocks are introduced in the tripping circuits. It is probably desirable to include some safety interlocking in certain schemes, but if by doing so they are made very complicated there is a danger that other hazards may be introduced. The company with which I am associated have for many years supplied busbar-zone protection in which stability has been obtained by an electrical bias feature instead of by safety interlocking. The scheme also allows of the use of a separate differential relay for each circuit-breaker, and so avoids the possibility of the inadvertent operations of one relay tripping all the circuit-breakers on a busbar. In some cases an additional safeguard has been introduced by designing the relays so that they will not operate until the switchgear framework becomes alive due to a busbar-zone fault.

The authors' alternative to the simple Petersen coil seems to have no outstanding advantage. Experience has shown that with correctly-designed coils there is practically no rise in voltage due to resonance, and, moreover, the voltage between the faulty phase and earth recovers slowly owing to the damped oscillatory circuit formed between the inductance of the coil and the capacitance of the lines. It is this latter fact which makes the Petersen coil a practical proposition.

It is doubtful whether high-speed auto-reclosing circuit-breakers could be successfully employed where the fault has resulted in a complete severance of the tie between the synchronous plants, but there is every possibility of its being useful in cases where the faulty circuit is not the only tie.

Mr. H. Trencham: I think it would be helpful if closer touch could be established between users and manufacturers in respect of the behaviour of supply systems and of apparatus connected with them. A complete knowledge of the cause of a disturbance must necessarily be a considerable step towards its elimination. I should like to see, for example, a sufficient number of automatic oscillographs installed on power systems to enable us to find out what happened during a fault. The information collected in this way would be much more accurate than that obtained from log sheets and the few instrument readings which are generally available. In this respect we lag considerably behind the United States.

I should like to ask to what extent the authors would expect that the arrangement shown in Fig. 3, which provides for easy maintenance and inspection, could avoid the necessity for busbar protection. It seems to me that busbar protection is even more necessary on gear of this kind than on the ordinary type of gear.

Some of the recently-suggested changes based on oil-fire risk would have the effect of militating against enclosure of switchgear. I think that the advantages to be derived from the abandonment of metal enclosure would be a heavy premium to pay against the risk of an oil fire. The designer of the arrangement shown in Fig. 4A has been at pains to provide quick removal and replacement of changed parts. I am not sure whether such elaboration is justified, however, because the advantages gained are those which are inherent in open-type gear. In gear for lower voltages it has been found possible to retain all the advantages of complete metal enclosure and yet at the same time to render the conductors reasonably available for attention in case of emergency, and I think the means whereby this has been achieved might well be examined in respect of the larger units of metalclad construction for power-station work.

As regards busbar arrangements, there is a great deal to be said for a simple single busbar ring for each station section, the sections being kept as small as possible and interconnected through tie reactors.

Finally, I believe that high-speed circuit-breaker action is the right way of dealing with faults, as it enables one to combat instability most effectively. Moreover, instantaneous reclosure of circuit-breakers is the right method of treatment when faults are, or can be made, self-clearing, but it may not be so effective on cable systems as on overhead lines.

The circuit-breaker shown in Fig. 19 is an arrangement for using the oil in place of the more usual cross-bar insulator, for obtaining a high speed of break. Pneumatic operation, however, is the primary source of the high speed, and as it is necessary to accelerate two pistons, a piston rod, and a considerable quantity of oil, I should expect that the aggregate of the mass to be dealt with is greater than with more usual designs. The design appears also to be subject to the disadvantages that the moving conductor would be difficult of access for inspection, and that energy has to be applied for both opening and closing the circuit.

Dr. W. Wilson: When Mr. Clothier's last paper* was discussed before The Institution I made a number of comments as regards the protective-gear section, and I am pleased to observe that several of the developments discussed in the present paper have proceeded along the lines I advocated. There is no need, therefore, to repeat my previous remarks as to the advantages of fully instantaneous protection. The use of unscreened pilot cables and also of "solid" core current-transformers are other features I have urged. The paper rather suggests that the solid-cored system for feeders is a novelty, but my own firm have employed it since 1920 and have never had cause to regret the decision.

I consider that the scheme shown in Fig. 11 is still too elaborate. If the authors would only use a biased system, they would secure a simple and therefore a reliable arrangement; and with this there would be a material gain in stability, through the possession of a floating

* *Journal I.E.E.*, 1932, vol. 71, p. 285.

fault setting, which is low for ordinary loads (at which internal faults usually originate) and high for through short-circuits. Incidentally, the authors seem a little nervous as to the stability of some of their schemes. For example, they double-bank their relays in more than one instance, on the principle that if one does not behave itself the other will save the situation; while in the system of busbar protection shown in Fig. 11 they avoid the decisive step of tripping the breaker by making the relay sound an alarm, although surely time is a vital factor in the case of a busbar fault.

I agree with the authors and with previous speakers that busbar protection should now be incorporated in the scheme of safeguards against interruption of supply. The busbars are the most difficult part of the system to protect, and, as Mr. Johnstone Wright has told us, they are in general very reliable; for these reasons they were left to the last when protective gear was being developed. Efficient and reliable busbar protection is, however, now available, and the scheme of protection should be made complete by including this feature.

Mr. L. Gosland: I should like to know whether there is in progress or projected in the immediate future any experimental work to supplement the theoretical study on which Fig. 2 is based.

The authors describe a cheap form of busbar-zone protection involving over-current and earth-leakage relays, and state that this suffers from, amongst other things, lack of discrimination. I should like to know whether this lack of discrimination is inherent in the system or whether it arises from the fact that we are not able to calculate the maximum fault currents with sufficient accuracy. There is no doubt that there is a great deal that we still do not know about system impedance under short-circuit conditions; for instance, it is a matter of considerable difficulty to calculate the current which would flow in an earth fault near a sub-station fed by several cables in parallel. In connection with such problems as this, as well as with others in which the E.R.A. are interested, there is great need for a series of short-circuit tests at representative sites, the use of such tests in this particular instance being that from the results obtained we can check the accuracy of the methods used to calculate fault conditions under which relays and circuit-breakers have to operate.

In Fig. 5 the authors show how a fault in an unprotected zone gave rise eventually to serious faults in other zones, and complete shutdown of two switch-houses. Complete protection of all plant, including busbar zones, would of course reduce the possibility of such a chain of events arising, simply by cutting down the time for which any fault is allowed to persist; but I should like to know whether the authors think that with protective gear covering all zones, faulty sections would be cut out so rapidly that the risk of such a sequence of events arising would be so remote as to be not worth while guarding against. There is no doubt that if the subject were properly investigated we should be able to find out exactly what are the stresses causing these consequential faults, and to prescribe means by which apparatus could be strengthened against them, but there is little point in making such a tedious investigation if action on the results of it is not going to be economically justifiable. A case in point is the sequence of events outlined in the authors' Fig. 5. The consequential faults there arising were due primarily, not only to the fact that the initial fault was allowed to persist, but also to the fact that the neutral earth-resistor, which was essentially the component protecting the system against such consequential faults, was not up to its job and had to be either protected or allowed to burn out. The above is an example of economic considerations dictating the installation of protective plant which it must have been foreseen would be inadequate in certain unlikely eventualities, when its failure would be bound to give rise to the consequential faults described.

Finally, with regard to the low-inertia, low-oil-content turbulator breaker illustrated in Fig. 19, one presumes that the amount of oil contained in the switch-tank proper has been reduced as far as possible, and it would be interesting to learn the authors' reason for using oil as the mechanical operating link and so adding appreciably to the total oil-content of the switch. It is of course appreciated that in the example illustrated the switch is used with oil-filled busbars, but presumably the switch could be used with other types of busbar, in which case the oil incorporated in the switch itself would be the only oil on the site.

Dr. C. C. Garrard: All engineering consists of reconciling different points of view, and if generalities are to be applied it is necessary to reduce them to a statistical basis. What I have in mind is very well illustrated by a letter I had recently from a friend of mine in the United States. The supply companies there desired to obtain exact information regarding the performance of oil circuit-breakers, and to this end they took a census of 24 000 automatic oil-circuit-breaker operations which had occurred in the 5-year period ending December, 1935. It was found that only in 1 case out of every 800 was there a serious unsatisfactory operation, and in less than 1 case in 2 400 operations was there an oil fire of any consequence. The American engineers regarded this record as excellent. I doubt whether we should be so satisfied with such results in this country, and I think that we could show a still better result. It would be very useful if we could obtain similar figures as regards busbar-zone faults, as they would enable us to judge better whether the added complications and cost of busbar-zone fault protection are justified.

Looking at the remarkable type of switchgear illustrated in Fig. 4A, I am reminded of the developments in the general design of high-voltage switchgear which have taken place in my own lifetime. About 35 years ago it was found that switchgear troubles chiefly occurred at the back of the switchboard, which was actually a switch-*board* in those days. Dr. Ferranti therefore proposed that we should employ switchboards without any backs. The next advance was to put the switchgear into boxes or cubicles, and to fill the boxes up solid with compound, so that the customer could install the switchgear and then forget about it. The switchgear illustrated in Fig. 4A seems to be a reversion to the cubicle type, as I presume the insulation of the parts consists of air. I notice that the authors have not given a name to this type of switchgear, and I suggest that they might call it the " jigsaw " type.

It seems to me to be going too far in the pursuit of accessibility to pull out the busbars when it is desired to see whether they are functioning satisfactorily. In my opinion a properly constructed busbar requires little or no maintenance.

I cannot quite understand the function of the duplex busbar-section isolating switch shown at the bottom of Fig. 3. When this switch is opened and earthed, it does not seem to earth anything in particular. If we consider one of the four switch-houses illustrated and imagine all the busbar-section isolating switches closed, then it will not be possible to open any one of them without first making the busbar dead—unless the isolating switch is placed in the half-cocked position, which is very dangerous.

Are the plug sockets in Fig. 4B of the air type? If so, I think they are very undesirable on 66-kV gear. If they are of the oil type, then they necessitate the use of increased quantities of oil, the reduction of which, I take it, has been the main object of this design. With this design, although the quantity of oil in the circuit-breaker proper has been much reduced, some of it has been put back into the operating gear. While the authors' pneumatic oil operation is very ingenious, I cannot see that it is in principle any quicker than the mechanical trip.

As air is used for setting the oil in motion, it appears to me that it would have been logical to use air to quench the arc, high-pressure air being a better arc-quenching medium than oil, even if the latter be contained in the best form of turbulator. If this idea were adopted the oil would be done away with altogether.

I regard the method shown in Fig. 5 of joining up two switch-houses as highly dangerous. The cable shown should certainly be protected by circuit-breakers at both ends. The best way in which this can be done is to connect the various sections together via a tie busbar, with oil circuit-breakers in the connections to the tie busbar.

I should be glad if the authors would indicate how the indicating lamps are connected in Fig. 11.

In the various busbar-zone systems of protection, alarm relays are proposed to be set lower than the master relays. While this scheme has been applied to cables, I doubt whether it is possible to use it with busbar protection. If busbar protection be used, the operating relays should be set as low as it is possible to set them, stability being attained by other means than setting the operating relay high.

The system of arc suppression by voltage injection shown in Fig. 15 is very ingenious and would, I think, have been justified during the life of the patents covering the Petersen coil; but as these patents have now expired the Petersen coil is much to be preferred, owing to its greater simplicity. I think Petersen coils will be used more and more freely in the future, on cable systems as well as on overhead lines. Experience is available which, if confirmed, will show that the Petersen coil when applied to cable systems adds considerably to the reliability of supply.

The subject of impulse testing is of great interest at present, especially in connection with transformers. For the usual forms of insulation used in switchgear, the impulse ratio is higher than that of the insulators on overhead lines. It would be very desirable, however, if standards for impulse ratio could be fixed.

Mr. W. A. Coates: The authors' remarks on voltage co-ordination must be interpreted with some caution. On overhead lines it is almost the universal practice to use insulators which when clean have a high flashover value in relation to the system voltage, the object being to get a good factor of safety when dirty. Switchgear or transformers having impulse-voltage characteristics co-ordinated with the characteristics of clean line insulation would be prohibitively more costly than standard apparatus. In spite of what Dr. Garrard has said, in my opinion it is essential on overhead lines to fit some form of high-speed spark-gap or lightning arrester.

Bridge tests of switchgear installations are to be preferred to periodical over-voltage tests, and most switchgear can be constructed in such a way that when it is being tested on site the units of insulation can be divided up into groups sufficiently small to enable one to make use of the Schering bridge. Provided then that such apparatus has been tested in precisely the same way at the time of manufacture, progress in insulation deterioration can be detected weeks before any breakdown can possibly occur, and thus an actual failure can be entirely prevented.

I am glad to find further converts to the idea of rapid reclosure of circuit-breakers to prevent outages. For some years past the Victoria Falls and Transvaal Power Co. have operated two of their transmission lines permanently in parallel and so arranged that, if a fault occurs, No. 1 circuit-breaker trips. This is then reclosed, and automatically No. 2 circuit-breaker is then tripped and reclosed. Originally a time-interval of 2 sec. was employed, but about a year ago this was reduced to 1 sec. and the results obtained since have been much more successful. The notion behind this method of working is that, the district being very much affected by lightning, when the transmission system is struck both lines are probably involved.

I should be glad if the authors could state whether the reclosing times given in Table 5(A) were obtained immediately following a tripping movement. With circuit-breakers like the authors', which are operated by a fluid, there is a considerable time-difference between an open-close motion and an open, stay open for a short time, and then reclose.

I am sorry that the authors have coined the term "pneumo-oil"; if we must have a special term, I suggest that "oleo-pneumatic" is preferable.

The remarkably short arc times given by the breakers referred to in Tables 3 and 4 are more characteristic of an oil-pressure or impulse type of breaker than of one which is operated by the generation of gas by the arc. It seems to me that these times can only have been obtained by risking much higher pressures within the arc-control device than are customary. If the authors have taken any pressure records within the arc-control device, I should be interested to see them.

Mr. P. Mathews: I propose to confine my remarks to Section (3), "Protective Systems for Short-circuit Faults."

On page 457 the authors state that balanced systems

of protection have given satisfactory service for protection of generators, transformers, etc., but that an exception exists in the case of power transformers with on-load tap-changing or with a high ratio of transformation. In such cases the authors prefer overload and restricted earth-leakage protection. At least one scheme of balanced current-transformers, known as "magnetic balance protection," is widely used for the protection of such power transformers. With this scheme the wider the transformation ratio the better, and tap-changing on load up to $\pm$ 10 % is readily taken care of without departing from the use of a simple type of relay. Fig. A shows the essentials of this scheme. Neglecting for the moment the feature that the high-voltage current transformer has its core divided into two halves, the simple magnetic-balance principle due to Fitzgerald appears, whereby the low-voltage current transformer produces in the high-voltage current-transformer secondary an m.m.f. exactly equal and opposite to that of the high-voltage primary. Thus the core of the high-voltage current transformer is not magnetized at all except when

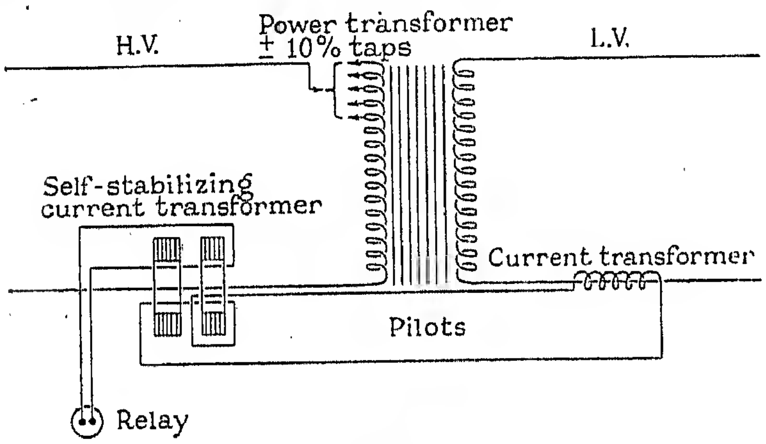


Fig. A

there is a difference between these m.m.f.'s due to the occurrence of a fault, so that the relay which is connected to a separate winding on the high-voltage current transformer is not energized, however large the through current.

Clearly it is immaterial how small the high-voltage primary current or how large the low-voltage, i.e. how wide the ratio of transformation. In fact, the larger the low-voltage primary current the better, since the low-voltage current transformers take the entire pilot burden. Further, it does not matter how large is the diameter of the high-voltage bushing current-transformer, or how large is its magnetizing current as a current transformer. Owing also to its being unmagnetized under stability conditions, high-permeability alloy of low saturation point can be used, giving excellent sensitivity.

Considering now the question of out-of-balance due to on-load tappings, which is the commonest practical case, the high-voltage current-transformer core is split into two equal halves (see Fig. A) with unequal numbers of turns. The average number is such as to give the requisite magnetic-balance m.m.f. described above. The difference gives an equal and opposite magnetization in the two halves, which is without direct effect on the relay since the two opposite induced e.m.f.'s cancel. The effective permeability, however, is so altered with increasing through current that the ampere-turns required to operate the relay increase more rapidly than those tending to do so, owing to the tap out-of-balance. At normal-load through currents the effect is to improve the sensitivity, somewhat in the manner of the compensated current transformer described by Messrs. Wellings and Mayo,* to whom this further development is due.

This scheme affords protection against inter-turn and inter-tap contactor faults, which the overload and restricted earth-leakage system, of course, does not. This principle is also extensible to the case of transformer feeders with h.t. circuit-breakers at one end only, where relays are required at each end of the feeder.

The authors are very properly concerned with the stability of busbar-zone protection, and there would seem to be broadly two causes of instability: (1) damage to, or failure of components of, the protective system; (2) wrong design of the current transformers or relays.

With regard to (1), this can only be dealt with by care in manufacture, factory and maintenance testing, and tripping by two sequential operations, using independent components; the chances against false tripping due to simultaneous failure of both being then enormous. In respect of independence, the Time-lock system (Fig. 13) seems superior to the Dualock (Fig. 12), which uses the same current-transformers for both.

With regard to (2), provided simple standard-type relays are used these will not usually be found in error, if correctly co-ordinated with the current transformers, but it may be that many engineers still have doubts of the possibility of correct current-transformer design owing to unfortunate experiences in the past, where attempts have been made to balance current transformers having a large magnetizing current (i.e. large compared with the relay setting), even including, in extreme cases, air-gap transformers. *A priori*, however, it is clearly better to design properly than to use a second line of defence against improper design, and there is to-day no difficulty in designing current transformers to give the requisite sensitivity and stability, even with the use of instantaneous-type relays and where a large number of circuits are connected to the busbars. In recent years, operational methods of analysis as introduced by Heaviside have become better understood, enabling a clear picture to be obtained of the conditions obtaining when a protective system is subject to suddenly-applied through currents.

Further, there are now testing plants in existence enabling oscillograph records to be obtained of the spill current and other electrical and magnetic conditions occurring under actual conditions of suddenly-applied large currents of the same magnitude as the short-circuit fault currents encountered in practice. Such experiments constitute a true and satisfactory operation test, and afford a definite measure of the stability margin available.

Mr. D. R. Davies: On page 448 the authors advocate the enclosure of all live conductors, and I agree that this is the first step to be taken to ensure continuity of supply; but I think it a pity they do not emphasize the additional precaution of immersing all these conductors and insulators in oil. It is not clear from the descriptions of some

* *Journal I.E.E.*, 1930, vol. 68, p. 730.

of their switchgear whether it is air-filled, nitrogen-filled, or oil-filled. Tests of insulation at the works will usually prove the quality of the material and the design, and if the conductors are immersed in oil subsequent deterioration can only depend on moisture absorption, which the oil will undoubtedly prevent. Oil immersion also avoids the frequent necessity for removing switchgear or taking it to pieces.

Regarding the layout shown in Fig. 3, I fail to find any feature which justifies the use of a mesh scheme for power-station work. Although the necessity of duplicate busbars for substations is sometimes doubtful, duplicate busbars are essential for a main station if the requisite flexibility in operation is to be provided.

I suggest that the authors should include in their reply to this discussion a section showing the design of Fig. 3 adapted for duplicate-busbar service.

I should like to know the function of the double earth switches shown in Fig. 3; they seem to earth each other. Nevertheless, no means seem to be provided for earthing the interconnecting cables or the reactors or the outgoing cables. Is it possible to earth the various components through the circuit-breaker, especially in the outgoing cables, and is it possible to apply a high-voltage test to the outgoing cables? I suggest that the authors should supplement the diagrammatic layout of Fig. 3 by a section through the switch-house, indicating their proposals for protecting control cables against fire hazards.

I am disappointed to find that the authors have adopted what they call " pneumo-oil operation." Tests show that it is possible to obtain 4 to 5 cycles' interruption with a conventional solenoid-operated breaker; and with such a design the contacts and other parts are more accessible than with the authors' new breaker. I hope that when the paper appears in the *Journal* it will contain oscillograms and short-circuit test data confirming the claims made for this design.

Mr. C. J. O. Garrard: Avoidance of faults is very largely a question of maintenance, and a considerable proportion of faults could be prevented from becoming dangerous were they detected when incipient. I have nevertheless heard the opinion expressed that it is better to build switchgear so that inspection is as far as possible unnecessary, because, it is alleged, accidents most often occur during inspection. I do not share this view, nor, apparently, do the authors, as they have gone to much trouble to adapt a metalclad construction (page 450) which is fundamentally not one that allows freedom for inspection, in such a way that one can take it to pieces and examine all the parts. This appears to me a somewhat troublesome way of achieving accessibility, which can be more easily attained by mounting the apparatus in cubicles, with doors for inspection.

Presumably one of the main advantages claimed for the gear illustrated on Fig. 19 is its compactness. Is not compactness a virtue that is somewhat overrated, particularly when, as in this case, it is attained at the expense of a very large quantity of oil? The financial advantages of compact gear are obvious, as is the fact that air-insulated cubicle gear takes up more space than oil- or compound-filled metalclad gear. I imagine, however, that the greater dispersal of cubicle gear may under certain circumstances be a considerable advantage, particularly in view of the unfortunately necessary air raids precautions. In the event of damage by bombs, or by the more ordinary hazards of service, a cubicle board would be easier to get into commission again quickly than a metalclad board, where the small clearances would prevent the use of improvised connections.

According to the authors' description of the gear illustrated in Figs. 4A and 4B, the piston in the lower part of the lower bushing is used to inject oil into the turbulator pot as the breaker opens. It appears that the volume injected must be very small, so that no strong blast effect is obtained. One would therefore only expect the injection to have much effect at quite low ratings. Is its effect at all considerable? The new circuit-breaker (Fig. 4B) has no visible latch for the moving contact, or means of indicating its position. Are the authors confident that if such a breaker were left closed for a long time there would not be a danger of the vibration due to the alternating current causing the moving contact to work open?

The results obtained with the arc-control pots fitted to the 132-kV breaker illustrated in Fig. 17 are remarkable. It would be interesting to know how the pot, which apparently consists of a number of plates held together by bolts, has been made to resist successfully the internal pressure, which, in view of the short arcing times, must be high. I have found that the presence of metal bolts in high-voltage arc-control pots is disadvantageous. Are the heads of the nuts and bolts in this case insulated, and in what direction are the vents to the pot directed?

In Fig. 17, on the right-hand side the end of the pot nearest the fixed contacts is shown covered with a plate in which there are a number of small holes. What is the object of these holes?

Mr. A. G. Lyle (*communicated*): The Petersen coil appears to be gaining favour for the protection of overhead lines at voltages even below 110 kV, and several authorities have expressed satisfaction as to its efficiency as a protective system. The voltage-rise on the healthy phase apparently does not cause such concern as earlier existed and which made resistance or direct earthing almost universal in this country.

One arrangement which may be of interest has been adopted on an overhead transmission system. The system is normally run with an unearthed neutral, but if one phase becomes earthed, thus increasing the voltage relative to earth of the remaining phases, a relay operates, after a time-lag, and connects the system neutral to earth through a resistance, and as fault current is then allowed to flow automatic tripping takes place instantaneously. The main circuit-breaker recloses and, as it does so, trips out the earth switch. If the unbalanced-voltage conditions persist owing to an earthed phase, the cycle of operations is repeated a predetermined number of times, after which the main circuit-breaker is left open and the neutral earthed. The advantage of the scheme is that during normal conditions there is an insulated neutral, whilst in the event of a temporary arcing earth on one phase no tripping need take place. On the other hand, if the earth persists it is turned temporarily into a fault condition for tripping purposes only.

Where oil-filled busbars are used, gas relays of the

Buchholz type offer a promising solution, avoiding some of the complication which attends differential systems where a large number of circuits are connected to the same busbar.

Mr. S. W. Melsom (*communicated*): Manufacturers of impregnated paper-insulated cables will doubtless agree

For paper-insulated cables operating at any voltage less than 20 kV the practice of cable makers is to adopt a maximum short-circuit capacity of 125 000 amperes per sq. in. for a fault lasting 0·2 sec. This limiting value is an inverse function of time, and for a short-circuit period of 1 sec. is reduced to 55 000 amperes per sq. in.

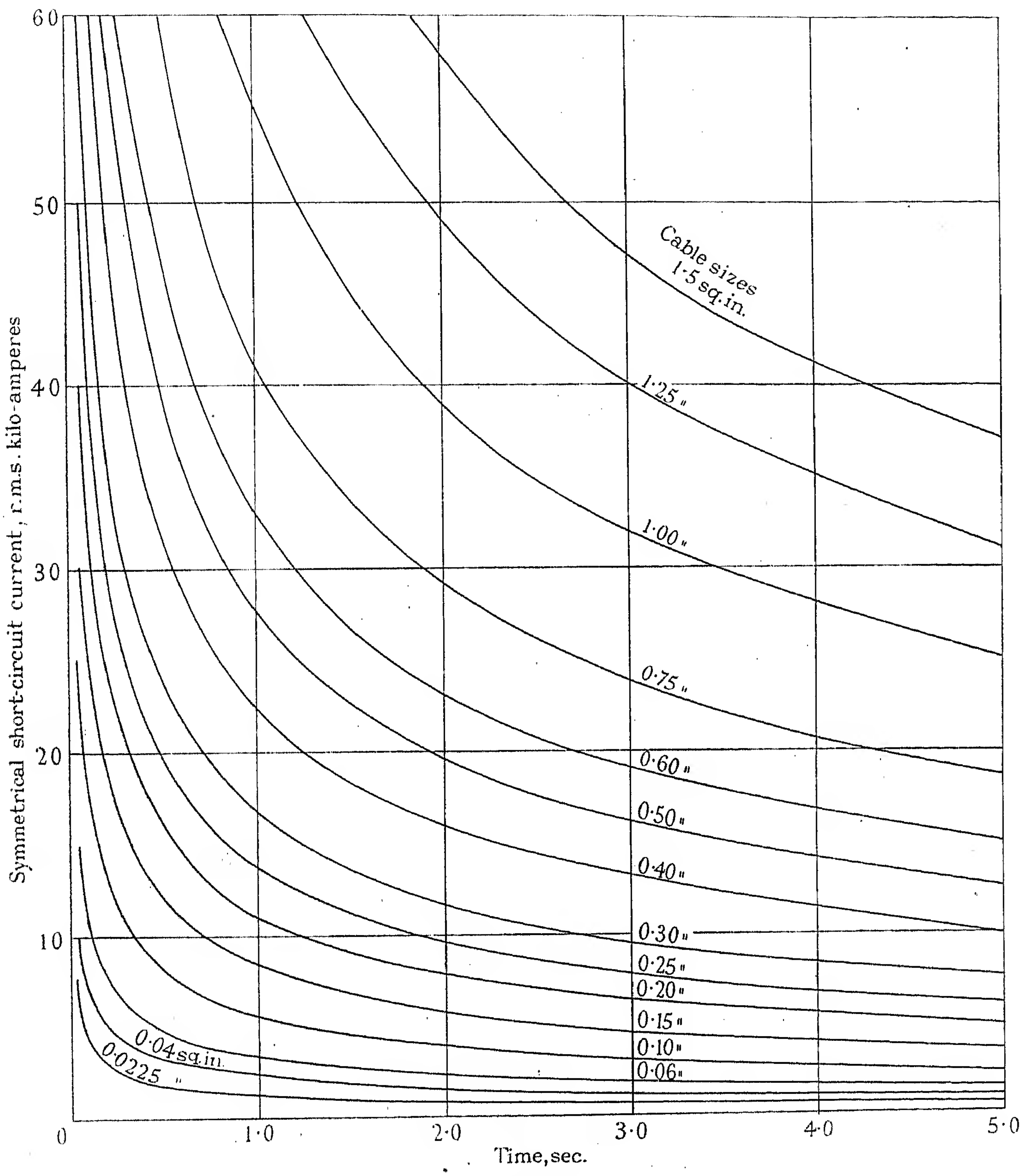


Fig. B

that a maximum conductor temperature of 120° C. is reasonable under short-circuit conditions. Fig. 2 has been based on the difference between this figure and an assumed maximum of 65° C. for normal continuous loading. The latter figure is lower than is now recommended, and consequently the short-circuit ratings obtained from Fig. 2 are somewhat high.

The safe maximum short-circuit currents recommended by the Cable Makers' Association for various cable-sizes and time-periods are shown in Fig. B. These values are based on the same conditions as those assumed by the authors, namely making no allowance for possible asymmetry of the short-circuit current and ignoring current decrement. A further important factor which

has been taken into consideration in formulating these recommendations is the risk of mechanical damage to the cables due to repulsion between the conductors.

It is interesting to note that reference to cable short-circuit ratings has recently been made elsewhere in the *Journal*.* The calculations in that case are based on alternative initial temperatures of 20° C. and 50° C., and are therefore still more optimistic than those quoted by the authors.

This is a matter on which adequate research is difficult owing to the numerous variables involved and the heavy test-currents required. It is to be hoped, however, that further data on this subject will be forthcoming, but in the meantime it is not considered advisable that the values obtained from Fig. B should be exceeded.

Mr. F. W. Rogers (*communicated*): The routine safeguard tests mentioned in Section (2)(B) of the paper are presumably the best for their purpose that the authors have found. They are tests that would be made, in practice, by the testing engineer attached to the "protective" or "relay" section of an undertaking's mains department. I suppose such tests would not be made frequently; on a large system, once in 3 months for each primary feeder and interconnector might be sufficient to keep the testing staff fully occupied. Most undertakings now have a less rigorous system that can be applied more often, and the authors' opinions on this system would serve to make clear both the lower and the upper limit of adequate testing.

In one undertaking every primary and secondary feeder (operating at 33, 22, and 11 kV) on a network that contains over 300 substations is tripped at each end in turn, and on each phase, by hand operation of every protective device that exists, every month. This sounds a comprehensive programme; and so it is. It is clear, however, that only the d.c. side of the protective systems is tested, and that a possible cause of trouble such as a "sticky" relay movement would not be revealed. If the oil switch does not trip on a certain phase a thorough examination follows, but irregularities between the protective current-transformer and the spindle that carries the tripping contacts do not show themselves in their true colours.

It is true that the d.c. half of the equipment is as important as the a.c. half; and that with the system I have mentioned the mechanical operation of the oil switches is tested, and station operators and outside engineers become familiar with protective relays more quickly than they would if they handled them only when the settings had to be changed. Yet the very large number of engineers who must be taken away from their other work, and the amount of alternative switching needed to carry load while feeders are out of commission, makes one doubt whether the end does justify the means. Is there a way of using the staff and the time to achieve a higher standard of testing somewhere between this and the best described by the authors?

Part—and, in my opinion, a large part—of the control engineers' and station switchboard attendants' salaries should be charged, in our thinking about these matters, to "continuity of supply." The title of the paper, "Safeguards against Interruptions of Supply," may reasonably include the operators as well as the gear they operate and the instruments that guide them. In the smaller stations—particularly when the outlook is smaller—these men are in an awkward position. Their normal lives are spent waiting for something to happen, but when it does happen the shift engineer, or a super control office, takes charge. The attendant performs his complete duty only when his superiors are absent or overloaded with work: that is, his experience of switching and relay operation is gained at precisely the time when he should be applying it. The problem is important enough because in some cases the chief control office is closed from about midnight until 7 or 8 a.m.—the period when switching for the benefit of the mains engineer is usually done. Is there a method of keeping men in a fit condition, alert and *au fait* with their system, between rare experiences of operating on their own responsibility?

Dr. P. F. Stritzl (*communicated*): On page 464 the authors refer briefly to arc-suppression by Petersen coils and, as an alternative, by voltage injection. It is claimed that the latter system achieves a similar effect without resort to a resonant circuit. I consider this to be impossible since the use of a resonant circuit is the feature of the Petersen coil which ensures the arc-suppressing effect, inasmuch as it prevents re-striking of the arc, and thus makes the occurrence of an arcing-earth impossible. It seems from Fig. 15(*b*) that the voltage injection without a resonant circuit causes the full line voltage to reappear across the arc space immediately after the arc is extinguished, and re-ignition is almost certain to occur under such circumstances.

Another aspect which the authors seem to have disregarded is the damage to line insulators following the discharge to earth across an insulator. With a Petersen coil this discharge is limited to one or a few half-cycles, and remains harmless. With the voltage-injection scheme, however, there is an unavoidable delay before the various switches are operated, and during this time the neutral is earthed through a resistance of comparatively low value, so that the insulator is likely to suffer before voltage injection is brought into play.

Furthermore, the considerable number of relays and switches seems to be a very undesirable complication and increases unduly the cost of the equipment. It seems, therefore, that the voltage-injection scheme, though perhaps preferable to solid earthing, is decidedly inferior to the Petersen coil method in more than one respect, and I can hardly believe that it will find much application. With reference to the Petersen coil scheme, the authors seem to take it for granted that only earth faults of a transient nature are dealt with without an outage, and also that its application is limited to overhead lines. General experience, in this country and abroad, on numerous networks, both overhead and underground, has proved conclusively that there is no objection from the operation point of view to applying Petersen coils on every type of high-tension network, and to making full use of their ability to continue operation with one phase earthed even for considerable periods.

On page 465, the authors refer to surge arresters and mention, as an alternative, an arc gap in combination with arc-suppression or auto-reclosing. Such a scheme

* Cf. J. H. Haws: *Journal I.E.E.*, 1938, vol. 82, p. 81.

would be liable to the development of rather frequent phase-to-phase faults, and I cannot imagine it being adopted. The action of modern surge arresters is so rapid, their price so moderate, and their discharge capacity so high, that any departure from this most successful piece of apparatus is more than unlikely.

Lt.-Col. W. A. Vignoles (*communicated*): The authors mention two routine "quality tests" of high-tension switchgear: (*a*) an insulation test with a Megger tester, and (*b*) a power-factor test. As regards the former, they consider that, while this gives an indication of quality, it cannot be regarded as a useful routine site-test for predicting the state and probable life of high-voltage insulation. The alternative power-factor test, they point out, has distinct limitations when applied to installations in service. There is a fundamental difference in the two methods of testing which is of very great importance. If an insulator is defective and the insulation resistance is low, a power-factor test on that insulator will disclose the fact. If, however, additional and sound apparatus is connected to the defective insulator, the power factor is improved, so that in a large installation the effect of a fault may be completely masked. When a test is made with a Megger insulation tester, however, if a defective insulator is in the circuit the addition of other apparatus of high insulation resistance does not mask the effect. The low resistance is not increased whatever apparatus is added.

The interesting question then arises as to what voltage should be used when measuring the insulation resistance of high-voltage switchgear. In Mr. Evershed's paper on "The Characteristics of Insulation Resistance," read before The Institution in 1913,* he proved that most insulating materials show a decrease in insulation resistance as the testing pressure is increased. It should be noted, however, that Mr. Evershed's tests were only carried up to 500 volts, and that there is considerable flattening out in the curve before that pressure is reached. The materials he was testing also were mostly of an absorbent character, and he proved that the variation in insulation resistance was due to the presence of moisture. Materials tested by Mr. Evershed that were entirely non-absorbent had a constant resistance with varying pressure.

Since Mr. Evershed read his paper, Megger insulation testers have been constructed for higher pressures, and instruments operating at 1 000, 2 500, and 5 000 volts are now available. Recently some tests were made on leaky condensers, and these showed the same insulation resistance when tested at 5 000 as at 500 volts. This may be due either to the non-absorbent character of the insulation, or to the flattening out of the curve.

It seems probable that the insulation used in modern high-voltage switchgear is almost entirely non-absorbent, and possibly an installation can be regarded as a homogeneous conductor of high specific insulation resistance. If this be so, there is no point, when measuring the insulation resistance, in raising the pressure above that required to get the sensitivity necessary for the high values of insulation resistance likely to be present. In this connection attention must be drawn to the difference between measuring insulation resistance and making a "flash test," in which the insulation is stressed in order to find weak places. Few engineers would care to make a flash test part of their routine, however valuable it may be when taking over new plant.

The 5 000-volt Megger insulation tester, which can be built to measure insulation values up to 20 000 megohms, has been asked for by engineers responsible for the maintenance of large 3 000-volt a.c. motors and other high-tension plant, but in these instances, no doubt, the insulation is of a slightly absorbent character.

Routine insulation tests of high-tension switchgear at 5 000 volts may, I think, be of considerable value if, as seems probable, faults in the insulation, such as a crack in an insulator, cause a decrease in insulation resistance within the range of the instrument.

[The authors' reply to this discussion will be published later.]

WESTERN CENTRE, AT PLYMOUTH, 29TH NOVEMBER, 1937

Mr. Harold Midgley: It is one of the penalties for the growing popularity of electricity supply that the effects of interruption of supply are becoming more and more serious, and too much stress cannot be laid on the necessity for taking every precaution against interruption, particularly of lengthy duration. Whilst interruption to ordinary power and lighting supplies is serious enough, a prolonged failure to a domestic consumer who may, for example, be relying on electric heating during illness, is likely to militate considerably against further use of electricity. A paper such as this is therefore very opportune, but I should like to see more detailed suggestions for speedy restoration of supply, a subject which is of course intimately connected with safeguards against interruptions.

Whilst I appreciate that the best possible medium must be used for closing switches, I assume that the use of electricity for this purpose has not been abandoned in favour of compressed air or oil without very detailed investigation, as such a decision reflects seriously upon the possibility of adopting electricity for many purposes for which it would appear to be highly satisfactory.

Any failure of supply to consumers may with advantage be investigated on the following lines: (*a*) How soon after the receipt of the information was the failure attended to? (*b*) What steps were taken to restore supplies? (*c*) What steps might be taken to avoid the recurrence of the failure? It has been found that an investigation on these lines, conducted not with the view of criticizing the steps taken but solely for the purpose of improving procedure in the case of future failures of supply, is extremely valuable.

Mr. T. W. Mackay: In view of the fact that all insulating materials are subject to deterioration, it becomes abundantly necessary to devise an efficient test which can be easily applied to installed equipment, and to make periodic tests to note the behaviour of particular insulation. For this purpose I suggest the use of a modification of the cymometer as devised by Fleming.

* *Journal I.E.E.*, 1914, vol. 52, p. 51.

This instrument is, in effect, an apparatus for measuring the frequency of electrical oscillations, and in modified form it has been used for classifying different grades of dielectrics.

In any elementary form of electrical circuit where the physical dimensions are constant the only variable will be the dielectric medium, and a change in this will in turn produce a definite change in the capacitance of the equipment under test. If the impressed frequency is gradually increased in the test circuit until the natural periodic condition has been obtained, which may be noted by the input to the circuit and by measuring the frequency, a figure of merit can easily be derived for the circuit and its associated insulation. This figure serves as a datum, and any departure from it in subsequent tests will give full warning that a change has taken place in the insulation.

I often doubt whether switchgear manufacturers as a whole are on the correct path of development with respect to the problem of rupturing a charged electrical circuit. In principle the modern switch differs in no way from those of earlier design; its object is to push or pull one piece of conductor away from or into contact with another, an operation which causes a chain of electromechanical happenings to follow in its wake. The radiation generated by the displacement of a number of unbalanced atoms in an electric arc may be the primary cause of disrupture failures of switchgear, since ionization is, if unrestricted, a condition of organic growth. I think it was Lodge who stated that a mass of 0·1 mg. moving with the velocity of light has approximately the same energy as a weight of 600 tons after dropping to the earth's surface from a height of 1 mile, and I submit that in an arc zone every condition is present for the liberation of energy of like proportions, sufficient to disrupt any switchgear tank, irrespective of its physical size or strength. In modern switchgear the arc is an accepted fact, and various ingenious attachments have been produced to utilize the resulting static pressure to displace the original arc and thus destroy its cumulative action and consequent effects. I think that a definite limit to present switchgear practice will soon be established, and the switchgear of the future will be designed in full recognition of the electronic principles involved. One has only to witness the ease and efficiency with which the grid bias functions on a rectifier under loaded conditions to appreciate that there is room for improvement in our present method of procedure.

I am associated with the development of the compensated reactor, which is designed to introduce, as quickly as the time-constant will allow, a reactive e.m.f. into the faulty or overloaded circuit. I have on record the evidence of a test where 250 000 kVA was available, and when this was short-circuited behind a compensated reactor the incident passed totally unobserved by the station staff.

The authors refer to the protection afforded to system apparatus by the introduction of a short length of underground cable, particularly where overhead mains are brought into substations. The actual amount of protection thus afforded is a matter of some doubt, since, by increment reflection from the points of surge-impedance change, the voltage builds up to its incident amplitude in 15 to 20 microsec., depending on the physical length of the underground main. I will admit that the cable produces a change in the steepness of the transient wave-front; but from a voltage point of view, and bearing in mind the very short time-intervals involved in the reflection periods, it is best to regard the arrangement as offering no protection, and my own experience and observation of terminal faults supports this point of view. To those who wish to go more deeply into this subject I would recommend Brewley's textbook.

Fig. C shows a new type of high-voltage fuse incorporating an arc-control device. The fuse in question is of the liquid carbon-tetrachloride, glass-tube type and the arc is quenched by a directed stream of the liquid. The fuse element A is fixed to the electrode B, which protrudes just clear of the steatite nozzle C. The spring, shown extended, is permanently fixed to the baseplate H,

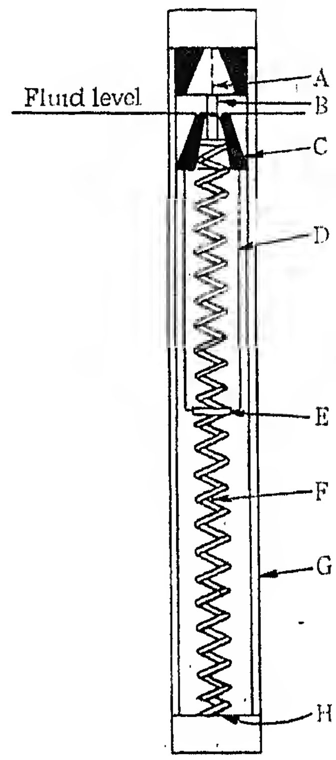


Fig. C

but at a point approximately halfway along the spring are attached the connecting arms G, which are attached to the steatite nozzle. The insulated nozzle is streamlined and so designed that, when the spring collapses, the fluid below the anode level is squirted through the throat of this nozzle into the space above. The action may be followed if it is realized that the point halfway along the spring will move with half the speed of the electrode when the fuse ruptures and the spring collapses. In consequence of the relative movement, the sparking tip or arcing electrode is rapidly drawn into, and through, the orifice of the nozzle, where it meets a stream of dielectric fluid which effectively chokes the arc and suppresses ionization.

Mr. R. W. Biles: Developments in switchgear technique are now strongly in the direction of high-speed action, and it is obvious that switchgear makers are accumulating so much knowledge of the performance of switches under short-circuit conditions that the additional burden due to high-speed action can be safely dealt with. Some years ago the tendency was to delay

the opening of the breaker as much as possible, in order to minimize the duty upon it. The development of high-speed tripping is very desirable on large modern systems with high interconnected short-circuit powers, involving the necessity for removing a fault in the minimum possible time so as to maintain the stability of the supply system.

On page 452 the authors state that site testing must necessarily rank as secondary to testing during the stages of manufacture. I hardly think that the latter can replace the site tests, for it is all-important to the supply engineer to know that insulation which has been in service for some time is maintaining its characteristics. I prefer the power-factor test: the principal object of such a test is not the detection of slight deterioration in individual insulators (although in some instances this is possible) but to make sure that there is no immediate danger of serious breakdown. Relatively high readings are obtainable on a milliammeter in series with a voltage-testing equipment when breakdown conditions are prevalent. Thus I know of one recent instance where a serious busbar fault was avoided when a routine voltage test had given a high milliammeter reading. Many manufacturers do not object to the application of 3 times phase voltage to earth.

The authors refer to testing equipment of 30-kV maximum test voltage. It is possible to obtain equipment, made up in two readily-transportable parts, which will give a maximum of 50 kV with satisfactory results, and deal with reasonable a.c. loadings.

On page 455, pilot systems are included in the category of high-speed protective gear. The success of this type of system depends upon the continuous or frequent checking of the condition of the insulation. Pilots can be a considerable source of trouble, and when they have broken down it is sometimes a lengthy, difficult, and costly process to locate the fault.

Inter-tripping schemes combined with a supervisory system of control have the benefit of constant indication as to pilot condition, and, provided the wires are laid totally underground, there is a minimum risk of indiscriminate tripping.

Carrier-current systems appear to have the advantage that pilots are not required and maintenance is confined to the terminal apparatus. I am disappointed to find no reference to these systems in the paper.

Fig. 9 indicates a margin of only $1\frac{1}{2}$ cycles between stability and tripping; this feature might lead to trouble on ill-designed gear. With present-day equipments the margins of time are none too great, and considerable improvements in design and manufacture will have to be realized to enable such small margins to be maintained.

From the authors' remarks on page 460 the general impression might be gained that all switchgear should be fitted with busbar protective gear. Some indication should be given as to the limit of power allowable behind the fault for which it is desirable to provide instantaneous clearance.

On page 466 the authors refer to auto-reclosing schemes for voltages above 100 kV; I think it remains to be established whether interconnected plant will fall widely out of step during fault disturbances when such schemes are employed. A safety device such as a synchronizing relay might be added to the equipment to prevent the reclosing of a switch unless synchronism is restored. Auto-reclosing schemes were in course of development 10 or more years ago in connection with group feeder schemes, and it is surprising that more use has not been made of this type of equipment, where one large circuit-breaker deals with the fault-clearing duty and is not reclosed until a smaller circuit-breaker or isolator has been opened, automatically removing the faulty section. With the quick-acting gear that is now obtainable it would appear that the interruption to a group of feeders could be reduced to a flick of the lights, and running machinery would not be seriously affected.

In the past it has been said that circuit-breaker design had not kept pace with turbo-alternator design. In view of the rapid strides that have recently been made in switchgear development that comparison is likely to be reversed in the near future.

In Fig. 2 the authors show the economy in cable size obtainable by utilizing quick-acting circuit-breakers. Any benefit which can be obtained in this way seems to depend upon the elimination of the overload relay; for as long as we have to depend upon it, even as a back-up, it is questionable whether any benefit can be gained.

Mr. R. C. Golding: With regard to the suggested types of busbar-zone protection, I notice that the authors suggest the initiation of the tripping sequence by means of current transformers. The current can only attain the required value after the potential has persisted on the switch frame for some time, as when the trouble commences as a high-resistance fault. Have the possibilities of obtaining quicker discrimination by means of voltage transformers instead of current transformers been investigated? If this idea has been rejected in this country owing to the necessity of insulating the switchgear from human contact, has this latter problem yet received consideration in any other country?

We have heard of developments in circuit-breaker operation which show that we must revise our preconceived ideas of the speed of "instantaneous operation." In timing these operations the authors speak of operation "within so many cycles." A better method of showing the conditions which the breaker must be capable of meeting would be by means of the curve of r.m.s. values of current flowing in the fault circuit. Here we have a curve of the usual steep-wave-front type, rising almost instantaneously to a maximum of 15 to 20 times the normal value, when armature reaction begins to take effect, and finally settling down to a value determined by the reaction of the fault circuit. Whereabouts on this curve can the breaker be made to interrupt the current? It is obvious that if the break can occur before the peak is reached, a much smaller breaker can be used.

Mr. E. Scriven: In Section (2)(B) the authors deprecate the use of over-voltage tests for routine testing because they are likely to strain any weak portion of the insulation. Nevertheless, it is probably best to test by this method on existing switchgear, as no other method can be applied to, say, the busbars of ironclad gear; and it is better to break down weak insulation artificially than allow the breakdown to occur under load conditions, and probably cause a serious fault and fire, with consequent shutdown.

With reference to quality tests, it is generally agreed that a Megger insulation test is in most cases practically useless, but it gives some degree of assurance of safety when time is essential and no method is available.

With reference to power-factor testing, this method is an ideal one, but is somewhat difficult to apply, especially to ironclad gear. Some measure of success may be obtained when testing spout insulators of the condenser type, but the method is of little use on ironclad gear when porcelain is used. The test is of great value for any insulator which can be isolated, e.g. open-type switch bushings, etc., and should be carried out at stated intervals or preferably with a varying voltage, up to about the working value, and the results compared with those of previous tests on the same insulator.

It is generally agreed that site testing can never take the place of works tests, but as it is impossible to test all equipment in the works, some form of test must be carried out on site, either just after erection or as a routine test. It is obviously impossible to test joints, which have to be made on site, in the works. I think an over-voltage test immediately after erection, before the equipment is put into service, is a necessity, and a power-factor test would be difficult with the present trend of design and the absence of any portable form of power-factor-testing equipment.

Mr. K. G. Glover: It is interesting to notice how closely interconnected nowadays are switchgear and protective gear; in this connection it would be interesting to know whether high-speed protective gear or high-speed switchgear was developed first.

With regard to discrimination curves such as those in Fig. 8, I would suggest that the curves should take the form of "bands" of definite width, rather than lines of infinitesimal width. The upper and lower limits of the "band" are determined by the consistency of the relay times when tested and retested many times under identical electrical conditions. When the curves are drawn in this way, the discrimination margin shown on the graph between relays at successive stations for a fault at any place is the actual margin under operating conditions. The desirability of relay characteristics being drawn as "bands" applies equally to other forms of protection involving time discrimination.

The authors state that site tests are secondary to works tests; while this is so in regard to switchgear, I suggest that it is essential to make provision for the checking of protective-gear characteristics on site. Those responsible for the maintenance of protective gear should be provided with adequate testing equipment.

I agree with the authors' contention that high speed of clearance of phase faults is very desirable. Unfortunately, however, it seems to be the most common practice at present to limit instantaneous zone protection to earth faults, leaving phase faults to be cleared by overcurrent inverse-time relays, which may take several seconds to operate. The authors appear to resign themselves to this in the case of on-load tap-change transformers and of busbars in less important stations. There would seem to be a field here for high-speed overcurrent relays.

With regard to busbar protection, it should be remembered that if stations are arranged on the "mesh" principle, as are all the grid substations in the South-West England and South Wales Area, all the conductors are included in existing protective zones without the need of separate busbar protection.

Mr. G. E. Parr: If on fault a large percentage out-of-balance full-load phase current is allowed to flow in the cables of the e.h.t. distribution network before outage takes place by means of the high-speed feeder protective system, how then is the *whole* phase winding of the alternator to be fully protected, seeing that the synchronous impedance remains constant and the earthing resistance from the star point remains unaltered? Do the authors consider that this is a case where to save the network one has to run the risk of damaging the alternator; and, if they have a remedy for this, what are the conditions under which the most efficient performance obtains?

How is the constant $1 \cdot 8$ obtained in the equation:—

Peak amperes = Symmetrical r.m.s. amperes $\times \sqrt{2} \times 1 \cdot 8$? Is the load factor as well as the form factor taken into consideration here? For example, with a load factor of 30 % and a form factor of $1 \cdot 45$*

$$I_{r.m.s.} = 1 \cdot 45 I_{av.}$$
$$= 1 \cdot 45 \times I_{peak} \times \text{Load factor}$$

Giving

$$I_{peak} = I_{r.m.s.} \times \frac{1}{1 \cdot 45} \times \frac{100}{30}$$
$$= 2 \cdot 3 I_{r.m.s.}$$

which is equivalent to writing

$$I_{peak} = I_{r.m.s.} \times \sqrt{2} \times 1 \cdot 627$$

Do the authors consider that possibilities exist for the improvement of the grid-controlled mercury-arc rectifier to such an extent that its advantage would be more pronounced than that of the high-speed system now under discussion? I have in mind the "mutator," whose relay can set itself so quickly that it will allow the load to continue if the short-circuit is only momentary, and if the short-circuit persists the relay can be made to keep a negative charge on the grids, causing isolation of the faulty section.

When dealing with transient-fault and excess-voltage protection one is led to consider the dielectric phenomena in high-voltage transmission. Would the authors kindly state whether more recent formulae than those evolved by F. W. Peek are now employed for the determination of the disruptive critical voltage and for finding the minimum spacing between overhead conductors?

Mr. G. W. Maxfield: I should like to deal with the aspect of the subject referred to on page 461 as "normal-voltage hazards."

First let me direct attention to the values of current possible in the hypothetical instance of two stations, A and B, running in parallel at extreme ends of 100 miles of grid line. Assuming that both stations are floating (i.e. no flow of active current in either direction) the charging kVA (approximately 8 000) may either be shared or be taken up entirely by one station. If it is equally shared we get the peculiar condition of the charging currents at the two feeding-points (approximately 20 amp. each) flowing in opposite directions in the same

* From Kelvin values in Cable Research Handbook.

line at the same time, there being zero current at 50 miles distance (middle of the line).

Next take into account the effect of the charging kVA upon the alternator regulation characteristic, the automatic voltage-regulator performance, and the supply wave-form. The last-named is particularly under scrutiny and depends on the amount of line charged, the kVA rating of the alternator, the load carried by the generator, the power factor of the local load, and the design characteristics of the alternator, usually determinable by the date of its manufacture. From a wide variety of combinations of line, load, and alternator it is found that the maximum distortion of wave-form takes place with the highest ratio (Leading kVA/Generator rating); that is to say, the longer the line carried, or the less the generator, the greater will be the distortion for a given orthodox design, undertaking power-factor, and in circuit (probably less than 20 % in terms of the alternator rating). The harmonics themselves thus predominate so long as the arcing continues, and any device calibrated on a frequency of 50 cycles per sec. is very liable to failure.

The exciter and automatic voltage regulator, too, are intimately involved during fault conditions, and in some cases an insulator flashover on a short line has recovered as a result of the clearing of a much longer line which was sound. This had the combined effect of (*a*) removing the peak value due to harmonics, (*b*) removing the "auxiliary" excitation due to the leading kVA of the long line. The sudden drop of voltage which followed enabled the faulty insulator to recover without it being necessary to disconnect it from the system.

As this phenomenon is to a large extent controllable so far as the charging points of the line can be located,

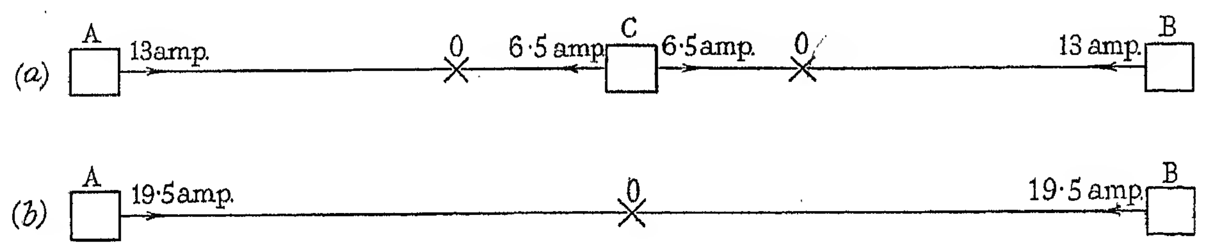


Fig. D

load. This effect is at a maximum at the charging end, and it follows that for any nominal voltage the instantaneous stresses on insulators cannot be the same throughout the length of the line.

This condition, which is most liable to occur, coinciding in time (of light load) with the worst atmospheric conditions of early-morning fog and frost, has on occasion been rather deceiving when it has been necessary to make a diagnosis after a line trip-out. When the insulators flash over and the power arc becomes established, the harmonics causing the distortion are sustained because the reactance to the higher frequencies is sustained, although the amplitude of the fundamental wave has collapsed in accordance with the impedance remaining all the new knowledge now being acquired on high-frequency apparatus might be put to account, using the harmonics to initiate the operation of relays. Referring again to the instance of two stations A and B (Fig. D) feeding in at the extreme ends of 100 miles of line, suppose that a third station (C) is run up to take its share of the charging kVA at the centre point. Conditions would then be as shown at (*a*) instead of (*b*), and there would be two nodal points instead of one, giving a quite different location of maximum stresses under both normal and fault conditions.

[The authors' reply to this discussion will be published later.]

TEES-SIDE SUB-CENTRE, AT MIDDLESBROUGH, 1ST DECEMBER, 1937

Mr. H. V. Field: One of the drawbacks of the Petersen-coil method of arc-suppresion is the need for readjustment of the choke coil when additions to the system are made. Does the alternative voltage-injection method suffer from a similar drawback? It would appear that adjustments to the injection transformer and earthing resistance become necessary under such conditions. Since the voltage to earth on both white and blue phases has the same magnitude when the red phase is earthed, what method is adopted to ensure that the unbalance-voltage relays act so as to select that voltage which has the correct phase?

Fig. 17, showing the arrangement of a circuit-breaker with rotary moving contacts, is interesting, as in the Newcastle discussion upon a paper dealing with the development of single-break circuit-breakers the rotary type was suggested by Mr. W. H. Clothier* as a type which would give the advantages of a double break together with symmetrical capacitance distribution, thus ensuring equality of voltage across each break. It is interesting to note that this type has also been found very suitable for high-speed operation.

[The authors' reply to this discussion will be published later.]

* *Journal I.E.E.*, 1936, vol. 79, p. 152.

NORTH-EASTERN CENTRE, AT NEWCASTLE, 10TH JANUARY, 1938

Mr. G. W. B. Mitchell: I agree with the authors that all apparatus installed in a system should be of adequate rating and performance to withstand the most severe conditions likely to be met with in practice, and that this adequacy should be proved by actual tests carried out under conditions of severity not less stringent than those which can occur in service. In view of this I should like to know whether the figures in Table 1 are intended to apply to the present or to the probable future, since I note that for a service voltage of 132 kV the maximum permissible short-circuit value suggested is 3 500 MVA. I believe that this figure, however, should read 2 500 MVA.* Assuming the latter is correct, do the authors consider that high-speed circuit-breakers of this rating can satisfactorily be produced and tested at the present time?

In connection with the effect of short-circuit current on cables, the theoretical relation between size and short-circuit current given by Fig. 2 may, I think, be misleading in practice, and I agree with the authors that, before any definite conclusions are reached, further tests should be carried out by the cable manufacturers in order to determine safe limits of operation. Assuming, for the moment, that the position may be serious in certain cases, we have to consider how the speed of operation of the protective equipment affects the issue. The authors suggest that high-speed protection will help matters considerably, but I rather doubt whether this is actually the case since, although it is becoming general practice to provide high-speed protection as a first line of defence, in the event of this failing, clearance of a fault is generally obtained only by operation of back-up overload relays, which, on large interconnected systems, usually have to be given a time-delay of the order of 2 sec. This means that the provision of primary protection of the high-speed type does not, in practice, ease matters appreciably, so far as the fault-current rating of cables is concerned. From other points of view, of course, high-speed primary protection confers many benefits, and the authors' contention that high-speed clearance of faults very considerably reduces system shock and damage at the fault has been amply confirmed by experience, particularly with large underground networks in this country which have been equipped for some years with high-speed pilot protection.

I was interested in the authors' film demonstrating the time it takes to start a fire in various types of apparatus when a fault is sustained. These data are, I think, important, since, when considering protective systems and especially busbar protective systems, it is very desirable to know the maximum time of operation of the gear which can safely be allowed. In certain types of protection it is still essential deliberately to time-delay the gear for one reason or another, and, although the experiments carried out by the authors are not sufficiently comprehensive to enable a schedule of maximum permissible times to be prepared, they nevertheless serve to give a useful indication of the probable order of magnitude of these times.

I think the wording of Item (E) on page 454 is rather misleading. The authors state here that supply systems including cables are not subject to excess voltages caused by lightning: I think that what they mean to say is that supply systems which do not contain overhead lines are not subject to such excess voltages.

I am glad to see that the authors define the terms which they use to describe the speed of operation of various types of protective gear, as confusion in this matter is likely to arise from the use of careless or misleading terminology. When reading foreign journals, particularly, one's attention is frequently attracted by some reference to high-speed protection, but it is often found on reading the article that there is nothing uncommonly fast about the operation of the gear described; and it may, in fact, be slower in operation than some of the normal gear to which one has become accustomed in this country during the last 8–9 years. I would suggest that the word "instantaneous" should not be used in the sense in which it is used by the authors, namely to denote the type of gear to which no time-delay has been deliberately given. The word "instantaneous" implies that the gear takes no time at all to operate. I suggest that all types of protection might be classed under two broad headings, namely "delayed" and "non-delayed."

I notice that all the times of operation of high-speed protective gear given in this paper are based on 10 times the minimum operating current. Although this basis is not actually misleading, I think that at least one other point on the operating curve is desirable, since the time of operation of most forms of protection increases with decreasing fault current, and it is desirable to know the time of operation with low fault-currents, which, on big systems, may still be of serious magnitude. In this connection it may be remarked that it is becoming common practice to state the time of operation of a circuit-breaker as its worst time on test, and not its best time; and since, for example, when dealing with distance-type protection, it is desirable to test the protective current-transformers for ratio up to the full fault-current rating of the circuit-breakers with which they are associated, I would suggest that the time of operation of the protective equipment should be stated at a current equal to 10 % of the breaker rating as well as at the figure of 10 times the minimum operating current suggested by the authors.

High-speed carrier protection will, I think, be the protection of the future on important overhead lines where the cost of pilots is still too great to be contemplated. The carrier system has many inherent advantages over protection of the distance type, one of the principal advantages being that carrier protection can be made to operate without complete reliance being placed on accurate quantitative measurements. High-speed distance protection involves many difficult considerations in this respect. Furthermore, carrier protection, owing to the fact that it works essentially on the "unit" principle, is not affected by the length of adjacent line sections, whereas protection of the distance type is.

There is a brief reference in the paper to the protection of generators, transformers, and reactors. Overall balance protection is, of course, extensively used, even on transformers fitted with tap-changing gear, but I

* Since corrected for the *Journal*.

feel that separate overload and restricted earth-leakage protection of the high- and low-voltage windings of transformers is to be preferred in all cases. Usually the best setting obtainable in practice with overall balanced protection is of the order of 50 % of full-load current. This can scarcely be considered adequate in the general case where the neutral point is earthed through a resistance designed to limit the earth-fault current to approximately full load. With restricted earth-leakage protection, a setting of about 20 % of full load can quite easily be obtained whilst ample stability is maintained on all through faults.

To my mind, the only advantage of overall balanced protection is that it gives rather quicker protection on phase faults; but phase faults unaccompanied by earth faults are usually uncommon.

I should like to suggest that we ought not to rush into a wholesale application of busbar protection right away. Quite a number of different schemes are in process of being applied at important stations in this country and I suggest that we should wait for 18 months or 2 years to see how these behave. The authors mention the question of " overlap " between feeder protection and busbar protection. This is an important point and it means that, if busbar protection is generally adopted, all switchgear manufacturers will have to consider the possibility of making provision for the installation of feeder-protective current-transformers on the busbar side of the circuit-breaker in metalclad gear. At the moment this can fairly easily be done in certain types of metalclad gear, but it is much more difficult to do in others. In outdoor switchgear there is, of course, no difficulty.

The authors suggest that frame-leakage busbar protection, although not applicable to existing switchgear, is particularly suitable for new gear. I cannot agree with this statement since, when one comes to look into the matter closely, the application of frame-leakage protection, even to new switchgear, is found to be much more difficult than one would at first imagine. I would, in any case, suggest that this type of protection should not be considered, by itself, for use in important installations. Some such system as Dualock is much more satisfactory from every point of view. Frame-leakage protection can, however, be satisfactorily employed in certain cases as a " check " feature.

I cannot quite see the advantage of the voltage-injection device illustrated in Fig. 15. It appears to me that this scheme would be considerably more costly than Petersen-coil earthing, which experience shows gives satisfactory results. In addition, the voltage-injection scheme involves the provision of apparatus containing moving parts, whereas the Petersen coil is a static piece of apparatus and therefore to be preferred. The only advantage which the voltage-injection system would appear to have over the Petersen coil is that, with the former, complete control of the recovery voltage is obtained. This advantage is theoretical rather than practical since, in point of fact, with Petersen-coil earthing the full displacement voltage is not reached until several cycles after the occurrence of the fault; and when the arc has been suppressed the faulty phase does not assume normal voltage to earth until after a lapse of several cycles. Judging by experience, this inherent time-delay in the Petersen-coil circuit is sufficient, and I do not think that further control of the recovery voltage is necessary. It may, in fact, be argued that the longer the faulty phase is held at earth potential the more chance there is of faults developing on the sound phases, owing to the " cock-up " voltage which is present under this condition. This flashing-over of healthy phases is one of the known disadvantages which accompany the use even of Petersen coils with their comparatively short time-lag action.

The authors suggest that when Petersen-coil earthing is employed normal protective gear should also be applied to the system, and if the arc-suppression device fails to clear the fault it should be short-circuited after a small time-delay, leaving the fault to be cleared by the normal protective gear. I myself agree with this method, although it is not the usual practice abroad. At first sight it may appear extravagant to provide for normal earthing and protection in addition to Petersen coils, but actually it is in general not extravagant since, in the first place, if continuously-rated Petersen coils and no ordinary protective gear apart from phase-fault protection are provided, sensitive directional earth-fault indicators are required on the system in order to provide a means of locating the fault; and, in addition, the cost of a continuously-rated coil is appreciably more than that of the short-time-rated type of coil which can be employed if the authors' suggestions are followed. Secondly, the scheme used abroad is more likely to give rise to double earth-faults owing to the fact that, if a fault on one phase is not cleared by the coil, the " cock-up " voltage on the system may be maintained indefinitely.

The authors' conclusions in regard to the best methods of economically obtaining both transient-fault suppression on overhead lines and lightning protection of station apparatus appear to be sound and logical, and if a totally-enclosed high-speed arc-gap can be put on the market at a reasonable price it should form a valuable addition to the group of protective devices which are at present available. Before the authors' recommendations can be fully adopted, however, more research must be carried out in connection with auto-reclosing of circuit-breakers. I hope that it will not be long before the manufacturers in this country are able to produce satisfactory auto-reclosing apparatus.

In conclusion, I notice that the authors emphasize the fact that proper attention should be given to important details, such as the protection of a system, in the planning stage. All too frequently systems are planned on far too broad lines in the first instance, and an attempt is made to add important auxiliary equipment at a late stage of development. Good results with this procedure can only be achieved by good luck. Whilst this truth may not have been so apparent in the past, when comparatively simple schemes were being dealt with, the advent of greater system complexity and the addition of such items as high-speed protection demand that this aspect of system design should not be treated casually.

Mr. W. N. Waggott: The various examples of switchgear layout given in the paper refer solely to metalclad switchgear, and the failure to give due credit to open-type switchgear detracts somewhat from the value of the

paper. In my opinion open-type switchgear, properly designed, applied, and maintained, ably fulfils in the sphere of high-voltage engineering the requirements emphasized by the authors as the first essential to reliability of supply. In some respects open-type switchgear offers advantages over switchgear of the metalclad type. The fire risk is less, and busbar insulation failures are less likely than with metalclad switchgear. For the higher voltages, open-type switchgear appears to be more dependable than metalclad switchgear, and a stage in voltage is reached when open-type switchgear alone is suitable. However much one may wish it were otherwise, it must be admitted that, using to the full the insulating materials known to-day, there is a definite limit of working voltage up to which metalclad switchgear is ideal and above which open-type switchgear of indoor or outdoor pattern holds the field. This limit of working voltage for metalclad switchgear may be found as the result of experience to be lower than is generally admitted to-day.

Fig. 2 presents a depressing view of cable-reliability prospects, as it suggests that no cable of reasonable section is serviceable. Experience has shown otherwise, as cable failures resulting from the passage of short-circuit currents have hitherto not been recorded, so far as I am aware.

I support the authors' statement that repeated application of over-voltage testing may weaken both sound and weak portions of insulation. In my view there is a tendency to-day to apply too many over-voltage tests to apparatus.

Dealing with protective systems for generators, transformers, and reactors, the authors record that there has been little fundamental change in recent years. Reference might have been made here to the use of gas-actuated relays, which are now frequently fitted to transformers and reactors.

I doubt whether any elaborate form of busbar-zone protection can be justified. If some indication of the condition of busbar insulation is considered essential, I suggest that for metalclad switchgear a leakage-to-frame testing and alarm installation will meet the requirements. For open-type switchgear, busbar-zone protection should not be necessary, as in the event of a fault occurring on such switchgear consequential damage of the fire-risk category is very unlikely. Leakage-to-earth testing and alarm equipment might be found of service on the circuit-breakers in open-type switchgear. In Fig. 10 an example is shown of frame-leakage protection in which the floor-reinforcing metal is to be cut away in the immediate vicinity of the grouting holes. It is bad practice to destroy floor reinforcement in such a manner, and I recommend for such installations that the reinforcement be so shaped as to clear the grouting holes, or that the bolts be insulated in some suitable manner.

The examples of high-speed circuit-breaker design described in the paper are ingenious, and I cannot see any weakness in their method of operation. I consider, however, that some further effort should be made to reduce to a minimum the quantities of paper and oil embodied in present designs of switchgear. Paper insulation is always a source of weakness in switchgear, and carries with it a grave possibility of electrical failure.

The general impression obtained from the paper is that the authors are ultra-cautious and recommend more safeguards than can be justified on technical and economic grounds. I submit that protective devices are by no means infallible and that over-protection, in addition to increasing the first cost and the maintenance charges, may actually result in a reduction of the reliability of supply.

Mr. W. A. A. Burgess: Figs. 3, 4A, and 4B indicate rather more complete access to busbars and to individual parts and insulators than that to which we are accustomed, but, as will be seen from the models exhibited, and from the description given in the paper, this is accomplished simply and without increasing the cost of the equipment. Though this has not been found necessary in the past with metalclad compound-filled switchgear, fluid insulation offers considerable economies and advantages with higher voltages, and the question of obtaining access to the various portions of the circuit then becomes relatively more important than in the case of compound-filled switchgear. Are the authors prepared to give an indication of the reduction in oil volume the new design affords? Reduction of oil volume is not of such paramount importance as some people think. Switch oil is a very useful cooling medium and an invaluable seal and preservative of fibrous insulation, and it does not burn readily unless it is atomized by spraying or by wick action.

I should like to know at what voltage Mr. Waggott thinks metalclad switchgear ceases to be economic. It has been successfully installed for voltages up to and including 132 kV, and, besides being a much safer construction than open-type gear, occupies far less space.

I should like to call attention to a recent paper by G. E. Heidenreich* which gives full details of a form of busbar protection of the leakage-to-frame type, applied to a very large 66-kV outdoor substation in America. The same paper also contains a description of an ingenious and apparently efficacious method of testing the insulation resistance to earth.

Regarding the question of protective gear generally, more attention ought to be paid to the provision of testing apparatus for testing relays and other equipment *in situ* without disturbing running connections.

Turning to Fig. 2, I believe that cable sizes smaller than those shown should not be deliberately adopted for a new installation. I am inclined to think, however, that enough is not known of the behaviour of buried cables under the high-current conditions equivalent to large-capacity short circuits, and that it could be proved by intensive research that the figures the authors give could be safely taken to represent 3-phase cables instead of single-phase cables. In any case, whatever economic considerations may demand with regard to long feeder cables, it would be folly to put in smaller cables than those indicated for short connections such as to generators and transformers, however small their rated kVA might be.

While I am prepared to support the authors' claims in Fig. 2 so far as new equipment is concerned, it is still with a query as to why the majority of cables already installed and subject to short-circuit currents equivalent to 500 mVA at 6 kV and 11 kV have not either burnt out or become damaged.

* *Electrical World*, 1937, vol. 108, p. 1864.

I find on reference to the Cable Research Committee's published data, from which I suspect the authors obtained the data for Fig. 2, that the natural impedance of the cables themselves imposes a restriction on the maximum through current of the order illustrated in Fig. E. If these curves are compared with those in Fig. 2, it will be found that the natural impedance of the cables reduces the maximum possible through current to values equivalent to those permitted by Fig. 2 for the shortest time in which the circuit could be cleared by instantaneous relays and fast-acting circuit-breakers in a distance varying from 1 mile for 0·05 to 0·1-sq. in. cable to ½ mile for 0·25-sq. in. cable. I think this is probably the chief reason why more cables are not broken down by through current, and that it should reduce any alarm caused by study of Fig. 2.

It may be of some interest also to note that safe values for current-transformer primaries in compound-filled metalclad switchgear appear to be of the order of twice those given in Fig. 2.

Earth faults, which probably form the greater majority of cable faults, are not likely to cause inordinate heating of cores supplying them if they are cut off within a reasonable time, since they are usually restricted by neutral resistances to values of the order of 2 000 to 5 000 amperes, in addition to the neutral earth-connection and fault resistances; but if they are not cleared reasonably quickly there is a possibility of the restricting resistance burning out and allowing much heavier currents to flow.

It would appear to be probable that a heavy earth-return current will seldom flow in the sheath of the cable supplying it, since the natural repulsion of currents flowing in different directions will tend to make it take a wider path, with the result that it may arrive at the station at which the neutral is earthed on the sheaths of other circuit cables. For this reason alone it would appear advisable to keep the earthing of cable sheaths separate from the main earth, to earth them before they enter the switch building, and to provide adequate earth connections.

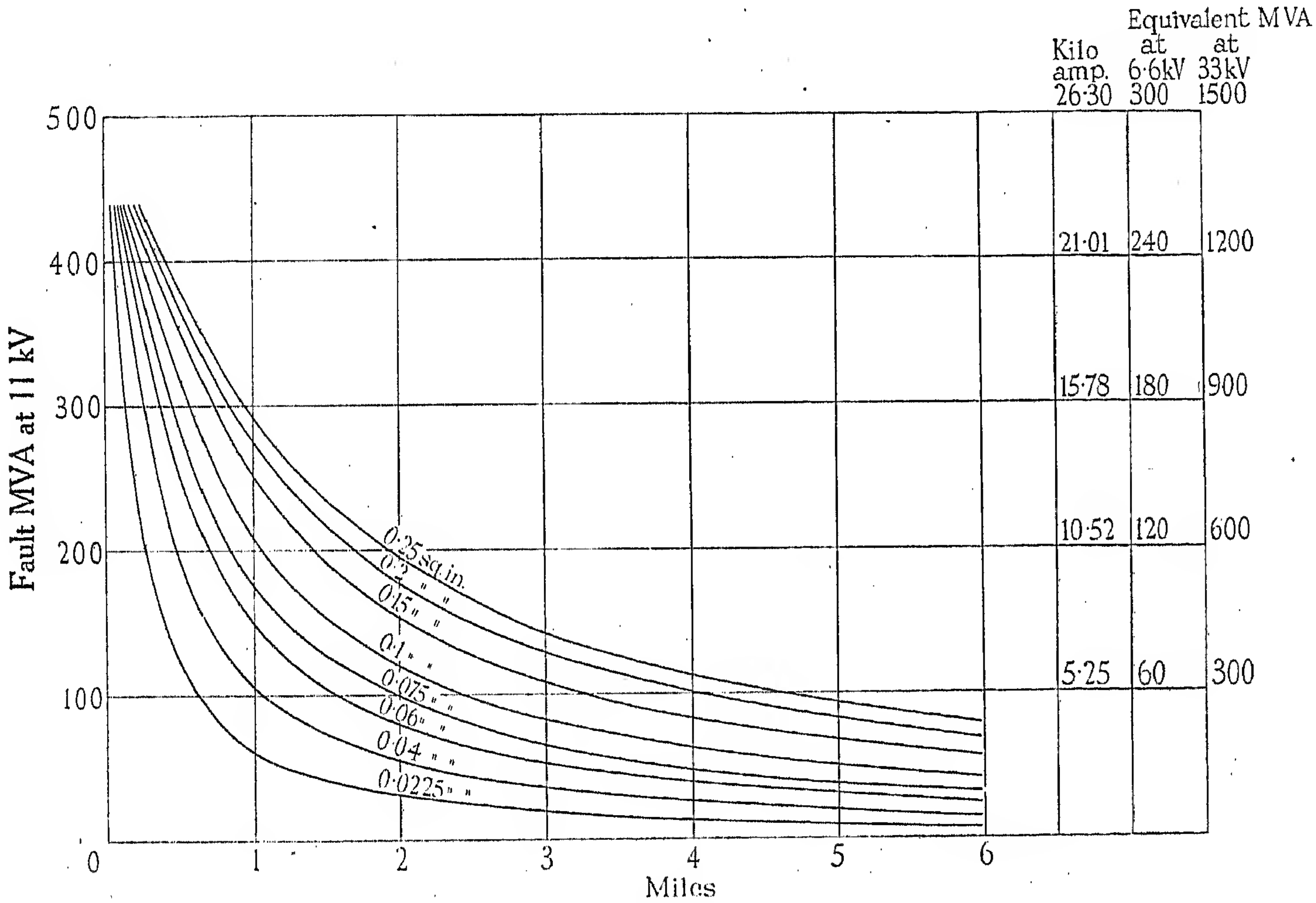


Fig. E.—Curves showing reduction of fault MVA by natural impedance of feeder cables.

It is interesting to note that temperature variation of the core within the limits given by the authors, namely between 65° C. and 120° C., increases the natural impedance of the cables by about 23 %, and reduces the maximum through current by about 15 %.

As the resistance component predominates in the effective cable impedance for 3-core cables, it is not surprising to find that the power factor of the circuit is improved materially under short-circuit conditions. For instance, the power factor of a 0·25-sq. in. 3-core cable is 26 % with a short-circuit at ½ mile from the source of supply, and 70 % if the short-circuit is 6 miles from the source of supply, with a maximum capacity of 500 mVA at 11 kV. This factor will effect a definite easement of the stress on the circuit-breakers controlling the circuits, and I should like to ask the authors whether they can assign a practical value to this easement.

Mr. W. J. Brown: I desire to refer to the question of routine site-testing of insulators. I support the authors in their condemnation of over-voltage tests and their preference for power-factor measurements. The latter, properly carried out and correctly interpreted, are of undoubted value in revealing a tendency to deterioration. For making power-factor measurements I prefer the use of a Schering bridge rather than the Doble tester mentioned by the authors.

I wish strongly to emphasize that routine power-factor measurements should be made at the working voltage of the insulator under test. I regard as unsatisfactory a standard test voltage of 10 kV for all ratings, and would hesitate to draw any conclusions from power-factor results obtained by testing at a voltage lower than the working voltage. The presence of internal ionization in an insulator causes the power-factor to be increased. Manufacturers of paper insulators make power-factor measurements at several different voltages and can tell from the increase in power factor the critical voltage at which internal ionization commences. This critical voltage must be higher than working voltage because it is important that in operation each insulator should be ionization-free. One effect of deterioration is to reduce the ionization voltage, and it should be obvious that measurements made at working voltage are required in order to reveal when deterioration reaches a point likely to be detrimental.

I realize the difficulties involved in making high-voltage tests on site, but, if routine site tests are regarded as important, switchgear can be designed to enable dielectric-loss measurements to be made with the apparatus alive and so obviate the necessity for a separate testing transformer. It is simply a matter of bringing out through shielded leads the earth connection of each individual insulator; this will no doubt add to the cost of switchgear, but it will involve no technical difficulties.

It is my experience that good insulators, free from ionization when made, are unlikely to deteriorate even over a long period of years, providing the power station is kept reasonably warm and dry.

Mr. F. C. Winfield: Mr. Waggott made one or two points which seem worthy of emphasis. Dealing first with Fig. 2, I would add that in the course of investigations of a large number of cable samples of all voltages and types which have been withdrawn from the ground, usually after faults have occurred, I cannot find a record of a single cable in which there was any charring or blackening of the paper insulation except in one instance where, owing to switch or other trouble, a short-circuit had been maintained for many minutes. I am therefore confident that the values given in Fig. 2 ought to be heavily qualified. The divergence from practice may be due to imperfect understanding of service conditions, but I would mention that I have frequently tried, without success, to find data concerning the charring limits of fibrous insulation under oil or other similar conditions as distinct from free-air conditions. I suggest that the absence of knowledge on this subject may have a bearing on the matter.

Mr. Waggott's second point had reference to the suggestions the authors make in respect to the insulation of switchgear in buildings. Reliance on concrete as insulation for fixing bolts, whilst practicable, is difficult, because it is hard to ensure that there will be no contact with reinforcing material. For this and other detail reasons I suggest that all matters of insulation of switchgear and independent earthing of parts of switchgear should, so far as metalclad switchgear is affected, be dealt with by the manufacturer in his works; i.e. that such insulation should form part of the design of the gear and should not be left to be dealt with on site.

It is desirable to point out that Doble has never suggested that a testing voltage of 10 kV applied to 33-kV of higher-voltage insulation would immediately reveal all incipient faults in such insulation; but, speaking with many years' direct experience of the testing of such insulation at 10 kV, he claims that original incipient faults do not imply a danger condition. He considers that these will slowly produce a growing deterioration which will ultimately reach a danger condition, and that his experience makes it clear that 10-kV testing will reveal such faults before they have reached the stage of danger. I believe that there is a great deal in his contention.

The authors themselves appear to ignore their principle in suggesting 33-kV testing equipment for 132-kV equipments.

They recommend auto-reclosing for 132-kV switchgear even where synchronizing is involved. I am in entire sympathy with their aims, but I do not feel that we have yet quite reached the stage of development where it is safe to make any immediate recommendations of this type.

Mr. R. W. Gregory: The paper contains two special items on which I should like to comment: (1) The development of the high-speed circuit-breaker for a.c. working, and its ultimate effect on system layout. (2) The general tendency to reduce the amount of oil in a high-power circuit-breaker.

Dealing first with item (1), the high-speed breaker has been in use for some 15 years on d.c. traction systems for feeder protection. Experience has shown that the quick removal of the fault from the system reduces the damage caused by the fault, and generally means that the line can be returned to service immediately. Lightning troubles on the Natal Railways some 15 years ago were cured by the use of high-speed d.c. circuit-breakers, because the high speed of break prevented the fault arc from doing any damage to the line insulation, and the line was therefore fit for service on reclosing.

A continuously good service has been maintained by the use of reclosing high-speed feeder breakers for d.c. traction work. Cannot equally good and continuous service be obtained by using high-speed reclosing breakers on an a.c. system? Assuming that high-speed breakers can clear a fault in 0·01 sec., and that reclosing can be carried out sufficiently quickly not to affect the maintenance of synchronism but sufficiently slowly to allow the conducting path of an arc to be cleared away, if one could devise an arrangement whereby reclosing on a fault was prevented, by some sort of "feeling-in" device, then the conditions which now obtain on d.c. traction service would also obtain on a.c. distribution and transmission systems, and the very simplest form of protection would result.

A device to prevent the reclosing of a circuit-breaker on fault is well worth the consideration of inventors, as it is reclosing on fault conditions that stresses the breaker unduly, and often settles its rating.

Turning to item (2), oil is rightly considered to be a potential fire risk, and it is argued that oil should be eliminated, or at least reduced in quantity. The oil-less circuit-breaker is practical politics, but it obviously introduces problems of its own.

Oil is not only a good insulator but a superior arc-extinguisher, and although it appears logical that reduction in the quantity of oil results in a reduction of fire risk, it does not follow that this is the case. The oil fire-risk is a function of the time and energy required to raise the oil to "flash point" when a switch is opening on fault, and to "burning point" when a fault occurs through or in the oil itself. The more oil there is the longer it takes for the same fault current to raise it to "burning point," and the more chance there is of the fault being cleared automatically or discovered and cleared by hand.

Cold switch oil is an excellent fire extinguisher, and a large volume of cold oil is, I suggest, much less of a fire risk than is a small volume of cold oil. It follows from this that in oil circuit-breaker design there is logically no need to give special attention to reducing the amount of oil if this is done purely to minimize the fire risk.

Mr. J. R. Kennedy: While laying the emphasis on high-speed operation, the authors still state that they rely on arc energy for arc extinction in their high-speed circuit-breakers. I should like to know whether it would not be preferable for the arc extinction to be controlled by external means, as is the practice on the Continent; especially in view of the fact that air and oil under pressure are stated to be available at the circuit-breaker for normal operation.

Mr. P. J. Ryle: In the development of the large high-speed auto-reclosing circuit-breaker, I imagine that many of our difficulties will be mechanical rather than electrical. The sequence of rapid opening followed by rapid closing will require high but controlled acceleration and retardation of moving parts in one direction, quickly followed by high but controlled acceleration and retardation in the other direction.

I should like to know whether the authors have ever considered the possibility of developing the rotary breaker shown in Fig. 17 in the following manner. If the turbulator pots and the moving contacts were made double ended, opening and reclosing could be effected by a single rotary motion involving acceleration and retardation, but without any reversal of direction. With pneumatic operation, in which operating pistons, valves, and buffers could be designed to give almost any required acceleration, retardation, and travel characteristics, it should be possible to obtain a very smooth and controlled action. Another advantage of the proposal is that, in any one complete operation cycle, "make" would take place at contacts inside a turbulator pot different and remote from that in which "break" had just taken place, so that there would appear to be little or no risk, from the point of view of the breaker itself, of reclosing too soon after breaking. The only limitations to speed of operation would therefore be mechanical ones. Of course, each successive complete cycle of opening and closing would require rotation in the opposite direction to that of the last previous operation, but, again with pneumatic mechanism, this should present no great difficulty.

[The authors' reply to this discussion will be published later.]

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 18TH JANUARY, 1938

Mr. R. S. Irwin: With regard to the question of the fire risk arising from sustained fault currents, I had experience of a fault which burnt out the oil in a cable sealing-bell but did not interrupt the supply. The switch protection was inoperative in this instance owing to a flaw in the construction of the trip mechanism. This experience emphasizes the importance of having thorough tests of switchgear carried out on site.

I should like to mention the protection afforded by tetrachloride fuses. This form of protection, where suitable, is, I think, very reliable, and I should like to have the authors' opinion of it.

Mr. F. Johnston: In connection with fire protection, have any experiments been made in the use of thermostats for operating overload relays, as a precaution against high temperature-rises in switchgear? A short-circuit will not necessarily cause sufficient current to pass to operate the relay, with the result that it is possible for an arc to form of sufficient duration to cause a fire before the current is cut off. On the other hand, a series of suitably-placed thermostats could be designed to act before a dangerous temperature was reached. At present, thermostats are used to operate fire-extinguishing apparatus; I should like to see them used, if possible, to prevent fires occurring.

Mr. E. N. Cunliffe: Among the "general safeguards" against interruptions of supply scheduled and outlined by the authors, I feel that one of the most important is that of establishing a suitable and efficient layout for the high-voltage distribution system. No matter how reliable the various components of a distribution system may be or how carefully operation and maintenance is planned and carried out, it is inevitable that a certain number of faults will occur, and these will result in interruptions of supply unless the distribution system is designed to prevent it. In my opinion a reasonable ideal to aim at is that a fault on a high-voltage cable should not cause any interruption of supply. This means that the distribution system should be an interconnected system, at least to the extent that every substation is fed simultaneously from two sources, and every cable should be provided with unit-type protective gear. Further, tail-end feeders and tees would not be permissible. This is an ideal rarely achieved, and indeed systems which were originally designed and laid out as interconnected systems have now been split up and are operating virtually as radial systems, thereby experiencing a larger number of shutdowns.

This state of affairs has no doubt been largely brought about by the rapid growth of available fault power on modern systems, coupled with the unavoidable de-rating of some of the older installations of switchgear. Another contributory factor is the natural desire on the part of the operating engineer to limit the extent of the area affected by the current and voltage surges consequent on a fault, a desire probably caused by experience with some of the older and less satisfactory forms of protective gear. It is often considered preferable to have a

localized total shutdown than an extensive system disturbance with no actual shutdown. The paper shows that there are now available types of protective gear and switchgear having high performance values, with which it is possible to construct a completely interconnected system, capable of clearing all faults without disturbance to synchronous machinery.

[The authors' reply to this discussion will be published later.]

IRISH CENTRE, AT DUBLIN, 20TH JANUARY, 1938

Mr. J. A. Butler: It seems to me that, instead of taking elaborate and expensive precautions to minimize the risk of fire due to the use of oil in switchgear, the most practical method of dealing with the problem would be to avoid the use of oil. The Electricity Supply Board have approached the problem from this point of view, and in the larger stations which they have at present under construction the use of oilless switchgear has been adopted. The most elaborate precautions taken against interruption of supply can be of little use if the human element fails and faulty operation results. In the larger stations mentioned, the Electricity Supply Board have adopted the use of compressed air for switchgear operation purposes; this provides great ease of operation but at the same time permits of simple and effective interlocking between the component parts of the switchgear, to prevent incorrect operation.

Mr. C. V. O'Donnell: I regret that the authors make no mention of the Buchholz relay, which can be considered to be the most effective protective relay for large power transformers. It has the following advantages over Merz–Price pilot-wire protection: (*a*) The Buchholz relay detects faults in the incipient stages and enables the transformer to be disconnected by hand before any serious damage is done. (*b*) It provides protection against inter-turn faults on one limb of the transformer, a type of fault which will not be detected by any type of balanced-current protection. (*c*) From the point of view of cost it is vastly superior to other forms of protection as it eliminates the necessity for duplicate current-transformers on either side of the transformer, as well as the expensive interconnecting cable. With the rapid development and use of the on-load tap-changing transformer, its advantage in cost becomes even more apparent, in that all forms of balance-current protection require complicated balancing devices to neutralize the out-of-balance currents which would otherwise flow in the protective relay owing to the varying ratio of the transformer on load.

What is the authors' attitude to inter-turn protection on generators? Merz–Price balanced-current type of protection would be insensitive to inter-turn faults on generators, and no alternative protection appears to be offered by British manufacturers. Certain Continental manufacturers provide automatic tripping of generators by utilizing the unbalance of the neutral-point voltage which occurs on an inter-turn fault. This practice would appear to be only applicable in cases where the neutral point of the generator is insulated, or earthed through a fairly high resistance. In cases where the generator neutral-point is earthed solidly or through a low resistance, some alternative method of detecting the inter-turn fault would have to be provided.

Mr. J. Higgins: The paper gives in graphical form the safe short-circuit currents for underground cables. This classical calculation is not of great practical importance as it would be too costly to work to where a city load, for example, had been connected to the grid network. Besides, public safety is not involved should the maximum short-circuit current exceed the "permissible" limits. What is of far greater importance is the short-circuit security of overhead lines, as the public safety is here involved.

Copper is still the standard conductor material for underground cables, but for overhead lines various materials are being used, such as hard-drawn copper, cadmium copper, Copperweld, galvanized steel, aluminium, steel-cored aluminium, and steel-cored copper. All have different physical characteristics and consequently different degrees of security under short-circuit. The importance of this matter is increasing owing, on the one hand, to the reduction of the construction standard via the revised ice-loading figure, and on the other hand to the tendency to use longer spans. Thus the security obtained on normal jobs without computation and solely on the basis of experience may not be obtained with new constructions.

Busbar protection is superfluous on a network substation such as that illustrated by the authors, as the switches in other substations on the network would come out for a busbar fault.

If steps are to be taken to eliminate fire risk, why not do so by the elimination of inflammable material from the substation by the use of oilless circuit-breakers, transformers, and cable-boxes?

Finally, if enclosed busbar construction is being retained, what experimental evidence can the authors put forward to show that the Buchholz relay would not give security? It is usual to try out the simple apparatus which is available before considering the more complex and hazardous methods.

Mr. R. C. Cuffe: I regret that the Petersen coil is dismissed so briefly by the authors, as very little literature is available in English dealing with either its operation or its construction. Regarding the alternative put forward by the authors, namely the voltage-injection system, there are several points which are not very clear:—

(1) In the vector diagram of Fig. 15(*a*) the impedance of the injection transformer appears to have been omitted when the direction of the fault-current vector I_F is determined.

(2) No vector diagram is given for the intermediate step when both S_4 and S_2 are closed. It appears that these switching operations might set up further disturbances.

(3) The rating and ratio of the injection transformer and the rating of the resistance are not indicated by the authors.

(4) From examination of the vector diagram in

Fig. 15(*b*) it is obvious that the magnitude of the earthing resistance will have to be altered when the length of the connected network is changed. It is not apparent that this alteration will be any smaller than the equivalent alteration required with a Petersen coil. Manufacturers claim that, with a properly designed Petersen coil, no trouble arises from (1) resonance voltages due to the high flux-densities in the core of the coil, and (2) that the recovery of voltage across the fault is kept low for a sufficient duration owing to the resistance damping in the coil and network.

In general, the proposed system would appear at a first glance to have the following disadvantages when compared with the Petersen coil: (i) More complex high-voltage connections. (ii) More elaborate plant, and hence, most probably, higher first cost. (iii) It entails moving parts, e.g. relays and switches. Thus the questions of wear and reliability of operation arise.

Regarding automatic reclosing of circuit-breakers, this appears to be a development which is as yet in its early stages as regards practical application to networks, but which would appear to have large future possibilities.

[The authors' reply to this discussion will be published later.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 24TH JANUARY, 1938

Mr. J. O. Knowles: I am pleased to note that the authors' recommended maximum permissible short-circuit values on various voltages (Table 1) confirm the figures I set down in briefer and more tentative form in a paper* last year. With regard to the normal-load currents given in the last column of Table 1, it is not clear whether 800 amperes is the recommended minimum normal current-rating of any 6·6-kV or 11-kV breaker or the minimum normal current-rating of breakers rated at 500 MVA and 750 MVA respectively.

Fig. 2 should be a very useful guide to minimum cable-sizes for safe working according to the short-circuit conditions possible. I have compared the current values given in these curves for a time of 0·2 sec. with those I obtained last year from the C.M.A., and find they agree closely. At the same time, I recognize that the authors have qualified the curves by their statements at the bottom of page 448.

I should have liked Table 1 to have included figures for a service voltage of 400 volts, and Table 2 to have been extended to cover the 3-core cables more commonly associated with the lower voltages.

I am glad to note in the paper a reference to incipient damage to cables due to their carrying short-circuits even for the short time required to open circuit on fault currents. I should like to see approximate recommendations (on the lines of Table 1 and based on Table 2) for the minimum sizes of cable which users should standardize on important distribution networks for various voltages —say, a minimum of 0·1-sq. in. cable on 11 kV, and so on.

As to the relative values of site testing and testing during manufacture, it is true that too much stress cannot be laid on the testing of insulation throughout the stages of manufacture, but even the best insulation after having been tested at the works does sometimes fail in service, and it is the failure in service which is all-important. The science of forecasting insulation breakdowns under service conditions is in its infancy at present, and I would only at this stage stress its importance.

I agree that faults may start as earth faults only, but it might just happen that the circuit-breaker was partly open when the earth fault became a phase-to-phase fault of much greater magnitude. I am told that some breaker failures have been at least thought to be due to such a coincidence, however unlikely it might appear to be. In modern breakers fitted with arc-control devices, the sudden change of conditions occurring with partly-open contacts might be very serious.

The fast-acting and pneumo-oil-operated high-speed breakers illustrated in the paper are developments of great value. It is interesting to note the adaptability of the arrangement of contacts and contact movement permitted by the use of modern arc-control devices. The horizontal movement shown in Fig. 17 cuts down the oil content as well as the operating time, and the single-break high-speed breaker shown in Fig. 19 has a minimum of weight in its moving parts and also in its oil content.

In this country we have not perhaps paid sufficient attention to the use of circuit-breakers which contain either no oil or only a tiny quantity of oil.

Mr. W. A. A. Burgess: It should be made clear to all supply engineers that when sectionalizing their systems they must provide for the maintenance of neutral earthing on every section under every condition of operation. In this connection, if the circuit at (1) in Fig. 5 were made through a circuit-breaker there would be a possibility of Switch-house A, together with the only neutral earth on the system, being separated from the fault earth, which would then persist as an arcing-earth passing capacitance current only and causing dangerous oscillations on the B system without passing enough power current to trip any circuit-breaker which might clear it.

The paper rather presupposes the universal use of metalclad switchgear, while this practice is very largely adopted at all voltages below 132 kV, there is a school of thought, notably in Liverpool, which prefers air-spaced equipment. I would suggest that the risks of outage already pointed out in the paper are accentuated with air-spaced gear.

I am not prepared to accept Fig. 2 as readily as does Mr. Knowles, as I consider that considerable further cable-research is needed before anything definite can be known of the actual performance of buried cables with through currents and times of the orders given. I would unhesitatingly accept Fig. 2 as a basis for new installations, but should apply it to 3-phase cables instead of the single-phase cables upon which it is based.

Mr. A. N. Mansfield: I quite agree with the authors

* *Journal I.E.E.*, 1937, vol. 81, p. 145.

that routine site-testing is of little use. A.C. voltage testing has obvious limitations, and d.c. tests are not favoured by switchgear experts. The cable manufacturers, however, favour them, claiming that they are non-injurious and give excellent indications of cable condition in expert hands.

With regard to power-factor tests, the present design of switchgear seems to limit them to outdoor gear.

The prevention of faults is of great interest when large overhead systems are concerned, and the voltage-injection scheme outlined in the paper seems to have two advantages over the Petersen coil, namely the elimination of tuning and the limitation of undue stress on the two healthy phases. I should like to ask the authors whether there are any data available as to its behaviour under service conditions.

Turning to the question of safeguards, every operation engineer will agree that a great reduction in the very large quantities of oil now in use is one of the most urgent needs. In Fig. 17 a breaker is shown with a shallow form of tank which is stated to give a 40 % reduction of oil, and in the switch depicted in Fig. 19 the oil is no doubt reduced still more. These reductions, however, seem to be incidental to the development of arc-extinction devices and increases of breaking speeds.

Mention has been made of the air-blast type of switch; it is a desire to limit the explosion and oil-fire risk throughout the whole range of high-voltage gear that has aroused such general interest in this type of gear.

Mr. L. C. Grant: The authors have subdivided the question of protection into what seem to me to be three classes: one is the arrangement of the gear, with subdivision of the busbars, feeders, and switches, into mechanical compartments; then there is the protective gear itself; and thirdly the development in recent years of several new types of circuit-breaker.

In the past the chief cause of trouble seems to have been either a busbar failure or an oil fire. In America heroic attempts have been made to isolate these troubles. I remember one American station where there were four separate switch-houses. In another case the three phases were isolated into three separate buildings, and even then the designers did not achieve what they desired, because a short-circuit developed over the mechanical operating gear.

The circuit-breaker business itself seems to be developing on the lines of the gas- and air-blast circuit-breaker on the Continent, and many new types of oil breaker in this country. I have a sneaking regard for the use of oil, not because it aids arc extinction but because oil is a good mobile insulating material. The chief disadvantage appears to be the danger of oil-vapour explosion and fire. Any oil in the neighbourhood of the arc itself will be vaporized and will produce an explosion when admitted to the presence of oxygen. It seems to me that one cannot get away from that danger, and so there is little to be gained by reducing the quantity of oil. If progress along this line is to be achieved the oil must be eliminated altogether.

In a paper* which I read before The Institution in 1929 I described a circuit-breaker and some tests carried out on it which produced an oil-less arc-extinguishing process. Some of the recent circuit-breaking devices resemble that breaker in appearance, but the oscillograph records suggest that the arc energy and stresses are greater.

A considerable amount of good can be achieved by some of the proposals put forward by the authors: for instance, in the paper an attempt is made to limit the amount of oil that can reach the arc, and to utilize whatever is vaporized to put out the arc.

In the method of protection against high-voltage surges, I am rather surprised to find the authors pressing the use of shunt spark-gaps. I have always thought that a spark to earth provides an easy path for power current, and thus the authors seem to be deliberately introducing a problem which switchgear designers have been trying to eliminate for the past 30–40 years. I fail to see how any type of air-break device, no matter how accurate it may be, can be relied upon to put out the arc. The action of certain special gaps and arresters is certainly ingenious, but some power current must be there and it will under bad conditions grow to undesirable values. It therefore seems to me that somewhere one must be relying finally upon the circuit-breaker.

A number of years ago a device known as the surge-absorber was developed and in it an effort was made to avoid a shunt path to earth while yet embodying the property of dissipating high-frequency and high-voltage surges.

[The authors' reply to this discussion will be published later.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 7TH FEBRUARY, 1938

Major A. M. Taylor: I will discuss safeguards from only one point of view, namely that of first causes of disasters. I have particularly in mind the question of generator stability and its association with quick-breaking switches. At no place in the world has more attention been given to this point than at Boulder Dam (U.S.A.). Huge issues were at stake, and extreme care was consequently taken with the stability calculations. On account of stability considerations it was necessary to cut down the output per transmission circuit to one-half, or less, of the desired value, thus doubling the transmission charges.

According to the paper (Table 3), a period of 5 cycles, from the moment of the start of the short-circuit, has to elapse before the arc is broken; the corresponding figure for the Boulder Dam breakers is 2·5 cycles. Again, the e.m.f. and kVA broken in the authors' case are 132 kV and 1 500 000 kVA, compared with 275 kV and 2 500 000 kVA on the Boulder Dam scheme. The authors must not be blamed for the fact that the voltage and current requirements in this country at present are less than abroad. In some of our Empire possessions larger values may be demanded shortly. I would add that still bigger powers may have to be interrupted, per circuit, on the Boulder Dam scheme in the near future.

There is some scope for progress in regard to the time that elapses from the moment of the first passage of

* *Journal I.E.E.*, 1930, vol. 68, p. 1089.

power current across a line insulator, consequent on a direct lightning stroke, to its ultimate extinction. The authors may say that the duration of the arc in their switch, in the circuit-breaker itself, only differs by a half-cycle from that in the Boulder Dam switch. But that is not the point. The real point is whether the damage at the insulator on the overhead line is not going to be tremendously reduced in consequence of those values of angular acceleration, under short-circuit, plotted against time, calculated for the Boulder Dam generators and a 270-mile line. An ordinary circuit-breaker, operating in $7\frac{1}{2}$ cycles, would open at the point C on the curve DCE.* Bearing in mind that the reactance drop in the stand-by line is momentarily doubled (where there is no line sectionalization), and making a fresh calculation for the diminished—but not cancelled

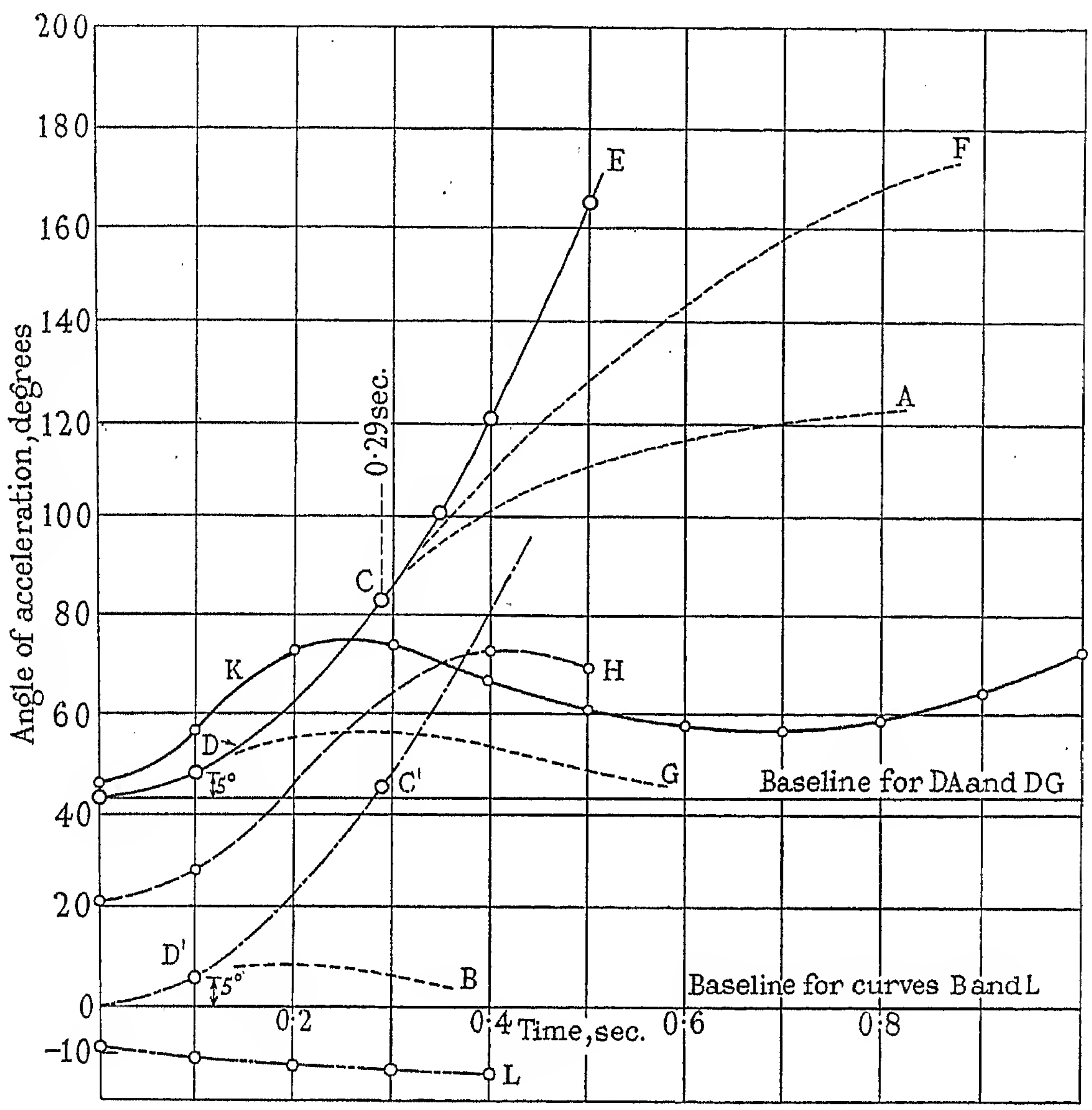


Fig. F.—Stability calculations for Boulder Dam scheme.

Curve DCE. Three-phase short-circuit of 240 000-kW 220-kV generating plant, initial load 250 000 kW. Calculations according to W. S. Petersen.
Curve CF. With a very long line (breaker has operated, but instability remains).
Curve CA. Boulder Dam line, 0·29 sec. (uncompensated), stability doubtful. Breaker operates at C. Line less than 300 miles long.
Curve DG. Boulder Dam line 0·10 sec. (without boosters); stability limit low, though safe. D is point where breaker should open a parallel line.
Curve D′C′. Quadrature boosters employed: calculations according to Taylor and Petersen.
Curve D′B. Boulder Dam line, using boosters; stability limit trebled by their use. This curve shows 40° advantage in stability over DG.
———— Two-phase fault to earth on 250 000-kW 220-kV generating plant, initial load 300 000 kW (Kronberg and McFerran).
— — — Two-phase fault to earth on 120 000-kW 154-kV generating plant, initial load 95 000 kW (Summers and McClure).
——- - —— Drop of motor angle (deceleration).

2·5 sec. saved by the Boulder Dam breakers. (It is granted that the conditions at Boulder Dam are much more severe than those that obtain in this country; but it is assumed that the authors want to meet any likely conditions anywhere.) If the authors had had to design for 275 kV they would have had an arc separation of the switch contacts of over double the distance; and the time would have been proportionately increased.

Referring to Fig. F,* the curve marked DCE represents —acceleration of the generator after the point C has been reached, due to this reactance, it will be appreciated that it is just "touch and go" whether the acceleration curve DCA is reached, or, still worse, the curve DCF. Even the curve DCA involves, as will be seen, a lead of the generator e.m.f. of 135° (120° + 15°) over the phase position of the receiver induced e.m.f.; and it is well known that a lead much exceeding 90° invites

* See also Report of the Paris H.T. Conference, 1937, Paper No. 118.

* Strictly speaking, the points D and C on the curve are incorrectly placed, but their relative positions are correct and do not affect the argument.

instability. If, however, as is effected by the Boulder Dam switch, the cut-off occurs at the point D of the curve instead of at C (the latter is nearer to that given by the authors' switch), the dotted curve marked G is obtained and the generator recovers itself and gets back to an angle of advance of 42°. According to the authors' data, given in Table 3, their switch would not open till the generator had accelerated to 62°, and, allowing for the upward continuation of the curve after the switch has opened, due to the doubled reactance of the line, there would be considerable danger of an angle of 90° being reached before the curve became asymptotic to the baseline.

Judging by communications I am receiving daily from transmission engineers in all parts of the world, serious ignorance prevails as to the conditions under which a station becomes transiently unstable. The calculations are unfortunately exceedingly intricate and laborious, and it may be helpful if I give a few approximate values, based upon the Boulder Dam calculations but contemplating the use of circuit-breakers of the ordinary type (say 9 cycles, overall), and for lines of various lengths and voltages. These figures may be useful, especially in connection with transmission lines of 66 000–88 000 volts and for lengths of 50 to 200 miles, of which there are very many in the Dominions and Colonies.

For 132 kV and 300 miles allow 20 000 kW per 2 circuits (half this for 1 circuit).
For 88 kV and 200 miles allow 10 000 kW for 2 circuits (half this for 1 circuit).
For 66 kV and 200 miles allow 5 000 kW per 2 circuits (half this for 1 circuit).
For 66 kV and 100 miles allow 9 000 kW per 2 circuits (half this for 1 circuit).

Dr. C. C. Garrard: The references included in Section (8) only go back to 1925, but the developments of which the paper gives some of the most interesting recent examples were of a much earlier date than this.

The first attempt to design safe switchgear was made by Ferranti in producing his cubicle construction, which to-day still has many adherents. The oil circuit-breakers of that time had insulated tanks, but since then the earthed-tank circuit-breaker has been much more largely used, although in the modern development of "oil-poor" breakers we have returned to the former type.

I suppose the design shown in Fig. 4B is of the oil-poor type, but as it uses oil in the operating mechanism and for insulating the busbars and spouts it cannot be said to have reduced the quantity of oil very much; if oil is dangerous, it is just as dangerous in the busbars as in the circuit-breaker. It is doubtful whether it is worth while to adopt the complicated design shown in Fig. 4B in order to get an earthed enclosure of the circuit-breaker.

The use of oil or compound for the purpose of insulating such busbars seems to me to be no longer justifiable, but the tee-off points from the busbars may still have to be insulated with oil or compound (if one does not adopt the cubicle construction). The busbars themselves, however, if constructed on the condenser principle, are absolutely reliable and, to all intents and purposes, fireproof.

Referring to the air-oil operating mechanism, I take it the authors will not claim that the oil used here gives any quicker operation, as the speed of operation is dependent on the speed of the piston in the air cylinder. The oil-operating rod is simply a means, I presume, of securing a compact form of mechanism. I am inclined to think that the supporters of the cubicle construction will find their faith strengthened when they examine the "jigsaw" type of switchgear illustrated in Fig. 4A.

It appears to me that the contact between the blade of the isolator and the bottom of the authors' removable busbar section cannot be inspected when in position, and this is the part which might go wrong owing to making bad contact.

I should like to ask whether with the arrangement shown in Fig. 4A it is possible to earth any circuit through the associated circuit-breaker.

I am very dubious regarding the desirability of the spark-gaps mentioned by the authors. If these are necessary, I should think properly-constructed lightning arresters would be best. Do the authors advocate these spark-gaps for purely cable systems as well as for overhead lines? I am inclined to the belief that any form of spark-gap which has no series resistance is likely to do more harm than good. The proposed spark-gaps are intended primarily, I take it, to protect transformers. Such a spark-gap, it is true, will chop off the crest of an incoming electrical surge, but the most vulnerable part of a transformer with respect to surges is the insulation between turns, especially the end turns. If the oncoming surge has a steep wave-front, of, say, a microsecond or so, this will stress the inter-turn insulation. The authors' spark-gap is no remedy; in fact, it may increase very considerably the inter-turn stress. This is because the chopping-off action I have just referred to results in the tail being much steeper than the front of the surge wave, and a steep tail also stresses the inter-turn insulation. This effect cannot occur with a lightning arrester which has series resistance, the effect of the series resistance being to stretch out the tail of the wave. I do not think transformer manufacturers will be very eager to adopt the spark-gap suggested by the authors.

On page 466 they say that "above 100 kV automatic reclosing of circuit-breakers compares favourably with arc-suppression schemes and is to be preferred." This statement, however, begs the whole question. The fundamental justification for the installation of arc-suppression schemes is the claim that thereby shutdowns due to faults are very greatly reduced in number, not only in the case of overhead lines but also for cable systems. Automatic reclosing of large circuit-breakers is somewhat dangerous, and especially when arc-control devices are utilized. All arc-control devices consist essentially of a small enclosure in which the arcing occurs. The oil in this small enclosure becomes carbonized and of low electric strength. If the circuit-breaker be immediately reclosed, there is danger of premature arcing occurring between the contacts, on the closing stroke. B.S.S. No. 116—1937 very wisely calls for a 3-minute interval between successive tests, which allows the carbonization to be dispersed and the electric strength restored. I am not saying that the 3-minute interval cannot be safely reduced—it can be—but there is a vast difference between that and a small fraction of a second. I think it unwise at the present time to advocate very quick

reclosing in large power stations as a panacea for preventing shutdowns. I think we should strike at the root of the matter and reduce the number of times a circuit-breaker is called upon to operate on fault; and it appears to me that the Petersen-coil idea gives the best hope in this direction.

Mr. W. R. Cox: On page 456 one system of feeder protection using pilots is described; reference is made to " solid " core current-transformers, whereas these current transformers actually have laminated cores. Since the majority of current transformers have no air-gaps, it seems logical that those which have air-gaps should be specified as such. This is particularly so because, for the last 20 years at least, there has been in use in this country and America a number of differential protective schemes using normal current-transformers. This is achieved by

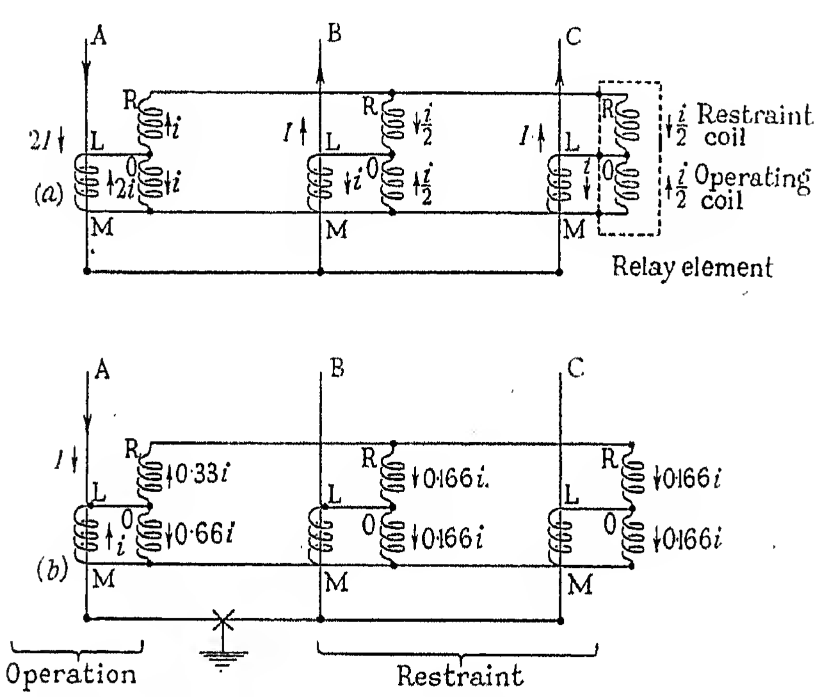


Fig. G.—Biased discriminating busbar-zone protection: single-line schematic diagram showing current distribution for normal condition.

(a) $i_0 = i_R$ in all cases; relays restrained.
(b) i_0 exceeds i_R in Relay A, and operation results. All circuits that feed into the fault are isolated.

the use of the principle of electrical bias, not mentioned in the paper. The provision of electrical bias gives a means of setting up the operating value of the relay as the load increases, which enables extreme sensitivity at low loads to be combined with complete freedom from incorrect operation upon the occurrence of heavy through faults. High-speed operation is also general. In this way complications such as special pilots, tuned circuits, and current transformers with air-gaps, are eliminated; in short, the reliability required is obtained with the simplest possible apparatus.

A typical application of a biased protective system is shown schematically in Fig. G. This system depicts a busbar protective scheme applied to a 3-feeder switchboard. The equipment required consists of three normal current-transformers and one 3-pole protective relay associated with each feeder. For simplicity, the diagram shows one phase only. The mechanical arrangement of the relay can take several forms, but probably the form which best illustrates the action of the relay is the beam type. Imagine a pivoted beam with a magnet armature on each side of the fulcrum and a set of contacts on one side. Each armature is influenced by the current flowing in the two coils. The one nearest the contact system is the operating coil, and the one remote from the contacts is the restraining coil. If the current in the coils is such that the pull on the armature in the operating coil exceeds the pull caused by the current in the restraining coil, the relay operates to close its contacts. Mechanically, the beam is arranged so that the relay contacts remain open when there is no current in the relay coils.

The diagram shows the current distribution in two cases: (a) when the system is normal, (b) when a busbar fault exists. In the first case it will be noted that equal currents flow in both the restraining and the operating coils of all relays. This gives stability, as the distance between the fulcrum of the beam and the restraining armature is greater than the distance between the fulcrum and the operating armature by a length proportional to the percentage bias. The relay contacts are therefore held open. Stable conditions also exist for faults in Feeders B and C, which may cause a heavy through feed to the fault. In the second case a busbar fault is assumed, and it will be seen that the distribution of currents is such that the operating coil of the relay associated with Feeder A passes more current than the restraining coil, and the relay operates to trip Feeder A. If Feeders B and C are outgoing feeders only, they are not tripped; but the tripping of Feeder A interrupts the power flow into the fault. If, on the other hand, either or both of Feeders B and C are able to feed back into the fault, the redistribution of the current in the relays associated with these feeders will result in these feeders being tripped also. Therefore, in all cases the power flow into the fault is interrupted.

Mr. John Walter Gibson: The scheme of arc suppression by voltage injection is very ingenious, and clearly has a number of advantages over the Petersen coil, particularly in that no adjustments have to be made for variation of the total length of line in circuit. On the other hand, much complication is entailed by the presence of apparatus operating at the system voltage; the four switches, which have to open under load, must inevitably be bulky and expensive.

With regard to the busbar-zone protection schemes, I am surprised at the authors' suggestion that the protective gear should not directly clear a fault at what is a vital point but should merely give a warning. This seems to show that the authors have doubts of the reliability of the apparatus.

Mr. J. S. Cliff: Referring to the pneumo-oil-operated circuit-breakers, shown in Figs. 4B and 19, which have been developed for high-speed fault clearance and suitability for auto-reclosing, the authors state that " the inertia of the moving parts has been reduced to merely that of the metal rod contact." Actually this is not so, since there is no latch between the contact system and the operating piston and coupling bar, so that these members also have to be accelerated whenever the contacts are opened or closed. I think considerably less inertia could be obtained by using an arrangement where-

by the contact system could be disconnected by means of a latch from the closing piston during opening.

A very important requirement of a circuit-breaker to be used for auto-reclosing is its ability to open without delay immediately after closing, so that the circuit can be cleared rapidly should the fault still persist. The pneumo-oil operation, as shown in Fig. 19, does not appear to fulfil this requirement very well; in fact, it is difficult to see how the circuit-breaker can open at all after it has been closed pneumatically, there being no means for allowing the air to escape from the cylinder once it has been admitted, as both valves only communicate with the pressure supply. Presumably two additional exhaust valves, not shown, are required to do this.

On a make/break operation the air would have to be removed from behind the piston before the contacts could be opened again, should the fault persist. As the protective gear will re-energize the trip coil in 2 cycles, the air must be removed in this time unless opening is to be delayed, with consequent lengthening of the fault duration. Should the breaker attempt to open before the air has been exhausted, the contact opening speed would probably be reduced and this might interfere with the correct functioning of the turbulator arc-control device. It seems doubtful whether the closing air could be exhausted in 2 cycles. The introduction of a latch would have avoided the necessity for doing this. It would be interesting to have the authors' views on this point.

In their suggestions on the layout of switchgear, the authors tend to overstress the desirability of access to components for routine inspection and show isolators and busbars arranged for easy examination. The circuit-breaker contacts, however, which probably need inspecting more frequently than any other part of the installation, appear to have been made the most inaccessible items. I think this is a retrograde step.

Mr. R. M. Charley: I should like to refer to one safeguard that is not mentioned in the paper, namely Buchholz gas protection for transformers. There are several types of fault that may occur in a transformer, against which the usual electrical methods of protection offer no safeguard, at any rate until the fault has assumed serious proportions. There may be an incipient breakdown of the insulation between turns: such a fault would have to grow for a long time before overload, balanced-current, or earth-leakage protection, would function. Overheating of the core may be taking place due to the breakdown of core insulation: this type of fault may result in very serious damage to the core before the electrical methods of protection give any warning of it. There is an example of a big transformer that actually caught fire while carrying load normally, and as far as the switchboard instruments indicated everything was in order. Insulation and ratio tests were applied to the windings and there was no sign of a fault. On inspection of the inside of the tank it was seen that there was a large volume of steel at the bottom, and this had been melted from the laminations of the core; but the windings were intact. To repair this transformer a new core was required, but if Buchholz protection had been installed, although the fault would not have been prevented the amount of damage would have been greatly reduced.

This method of safeguarding is well justified on all large transformers for normal service, and it is valuable for special cases such as voltage regulators, earthing transformers, and reactors, where it is difficult to apply the usual electrical protective schemes.

Mr. William Brown (Birmingham): Dr. Garrard mentioned the use of spark-gaps, and I should like to refer to our experience of them on the grid. Like all other undertakers, we have had some lightning trouble, but the trouble we have experienced with the 132-kV system has been less than that which has been encountered on the lower-voltage lines. In Central England, where we started to operate in 1931, although we have had an average of 3 or 4 trip-outs a year on the 132-kV lines, due to lightning, we have had only one instance of damage to apparatus, and that was damage to the end turns of a transformer. Similar damage has occurred in other areas of the grid, but the instances have not been numerous. As a matter of experiment we have fitted co-ordinating gaps similar to the spark-gap shown on the authors' model, but our experience has not been sufficient to enable us to pass an opinion as to their value. Having seen the experiment carried out by the authors, it makes one wonder whether they are of any use. I have asked a number of engineers who have fitted lightning arresters to express an opinion as to their value, and all they can say is that they have had no more trouble since they put them on than they had before.

Dr. W. Wilson: There are two points which I should specially like to commend in what may be called the general policy set forth by the authors. First, I agree with their insistence on protective gear being applied to every part of the circuit, including the busbars, in order to cut off the trouble at its source. My own firm has produced busbar protective schemes for at least 7 years, but supply engineers seem to have regarded the busbar as something so reliable that it did not need protection, and in consequence it has been difficult to persuade engineers to adopt such schemes.

The second point is with regard to the avoidance of unduly large currents. Now heavy currents, both normal and breaking, are due to the use of too low a voltage. It is difficult to understand the conservatism which prompts users to adopt the lowest possible voltage, apparently with a view to the reduction of danger from shock, when inconvenience and even danger from other sources are greatly increased thereby. In the first place, voltages up to 132 kV are commonplace to-day, and the design of insulation, spacing, and apparatus generally for dealing with high potentials is well understood and standardized. In the second place, an a.c. voltage as low as 400 volts is a fatal one, and low voltages are moreover responsible for more than their share of accidents owing to the greater risk of a leak not tripping the breaker. It should be emphasized that nearly all the trouble that can cause the switchgear to fail is due to current and not voltage. The production of gas in an oil circuit-breaker is at the rate of approximately 4 cu. in. per kW-sec., i.e. it is proportional to the square of the current. Thus a needlessly high current brings about increased gas production, which tends to cause flame-throwing and bursting of the tank. Mechanical forces are also proportional to the square of the current. They

tend to force the insulating posts apart, to distort the cross-bar, and to cause the trip gear to fail. Furthermore, if a normal current exceeding about the figure the authors mention, i.e. about 2 kilo-amperes, is employed, the contacts become so extensive that the clearances are encroached upon, while overheating of the tanks and cubicles becomes noticeable.

[The authors' reply to this discussion will be published later.]

EAST MIDLAND SUB-CENTRE, AT LOUGHBOROUGH, 8TH FEBRUARY, 1938

Mr. G. Caton: In reference to the section of the paper dealing with high-speed automatic-reclosing oil circuit-breakers, I note that the authors deliberately provide a high-speed means of detection and interruption to respond to a fault of a transient nature. If they regard 10 cycles as an ample period of time in which to clear a fault of such transient characteristics, then I question the justification of opening the circuit under such extreme conditions, particularly when the circuit-breaker itself, owing to its high-speed interruption, will probably produce line surges equivalent to those produced by faults of that nature. I am rather inclined to think that a circuit-breaker of a more normal operating speed would not respond to such faults, which are frequently the result of twigs falling temporarily across the line, squirrels, etc.

The tendency of the paper is towards increased costs of switchgear, but as the tendency is towards an ideal I do not wish to criticize adversely the various types of switchgear submitted in the paper, beyond reminding the authors that each additional accessible electrical joint and each additional piece of mechanism provides another link in the chain of potential trouble.

To produce a high-speed interruption of supply by means of an oil circuit-breaker one has to resort to special arc-control devices, on which the circuit-breaker functioning primarily depends. With this in mind I would refer to Fig. 17, showing horizontal turbulators, and would ask whether the authors have had experience of a carbon or a metallic path along the inner horizontal surface of turbulators after a number of short-circuit operations. This would have the effect of projecting the fixed contact towards the orifice of the turbulator, with consequent deleterious results. What period of time is required to overcome the inertia of the rotatable mass of this type of breaker?

Referring to oscillograph record No. 26729 (Fig. 18), it is notable that the pressure wave has a rather peculiar characteristic in that there is a distinct rise and fall of pressure after the period of arc extinction. I should like the authors' observations on this point; possibly it is in the nature of a pressure wave projected from point to point and eventually reacting upon the pressure-recorder transmitter.

I still think that present designs of automatic protection leave much to be desired. In connection with the more elaborate systems installed in recent years it is interesting to consider whether the relays will continue to receive the degree of maintenance which they demand and are presumably at present receiving. For this reason I would make a plea for absolute simplicity of protection. The more sensitive and complex the relay the more mechanically unstable it becomes, as the slightest foreign matter can interfere with the operation. A sensitive relay frequently demands an intermediate relay, which means another link in the chain.

The average induction relay imposes an extremely heavy burden on the current transformers, particularly on low earth-leakage settings. There are many such relays in service which if accurately tested with the co-operating current-transformers would produce a characteristic curve of an entirely different order from that corresponding to the relay only. For this reason I strongly support the use of instantaneous protective relays and reasonably high earth-leakage settings, and I therefore welcome the tendency shown by the paper towards relays of the attracted-armature type. This type of relay has a decided advantage over the induction-disc pattern inasmuch as the imposed burden is very much reduced and on the average the relay is more stable.

With regard to directional relays, both of the type which the authors describe and also the induction-disc pattern, these have the disability that a failure of the potential supply seriously disables the relay. Such a failure need not necessarily be caused by a faulty voltage transformer; it might be the result of an unsuspected blown e.h.t. or l.t. fuse. I consider that directional relays could with advantage be so arranged as to become operative as non-directional relays in the event of failure of the voltage supply.

I look forward to the authors' Utopia—to the time when all faults will commence as earth faults, in consequence of the earthed metal shrouding of all phases throughout the whole supply system. If an authoritative recommendation were made to the industry to this effect, we might look forward to the time when our protective problems will be greatly simplified.

We may regard busbar-zone protective schemes generally, along the lines which the authors put forward, as necessary evils, but if we must have such schemes let us by all means have them fully automatic and instantaneous. I am not enamoured with the proposed interim period for busbar protection to be of a semi-manual type. On page 458 the authors state that " protection against earth faults only is provided, since switchgear construction usually provides that busbar-zone faults originate only as earth faults." I am inclined to disagree, and I would ask whether the authors can justify this statement. Also, what are their recommendations for dealing with phase-to-phase faults, particularly as they do not greatly encourage the use of the ordinary type of overload relay for this purpose, on a score of lack of discrimination?

Mr. B. Nuttall: Table 1 is very important, and I should like to see the range extended to cover low voltages. The lower-voltage range should distinguish between permissible limits for normal domestic distribution networks and for power-station auxiliaries and the like. The limits outlined make it very evident to me that higher voltages must be used for city distribution systems and that supply authorities would find it better to do this

and stand the additional transformer losses rather than increase the rupturing capacity and therefore the consequent risk and expense of higher-power switchgear. The figures give added significance to the short-circuit forces available on consumers' premises and also give much food for thought where hand-operated mechanisms above 100 000 kVA at 11 kV (or equivalent short-circuit current at other voltages) are manipulated by consumers' engineers.

The limits of making and breaking currents given at the bottom of page 448 will, if consistently applied, limit the tie-in of grid-transformer capacity to selected stations, and will necessitate closer correlation of protective-gear settings in the selected stations with respect to those of the grid. A later section of the paper shows clearly the need for rapid-acting breakers and protective gear on the grid 132-kV network, which, properly applied, should free the local system of the selected station from outside disturbances. This is rightly so, as the local system has a higher percentage cable capacity and is immune from various atmospheric disturbances to which the grid is subject and for which various palliatives are submitted by the authors.

Referring to Fig. 4A, it is not clear what is the object of the current transformer shown in the circuit connection, but on the busbar side.

The authors state (page 452): "The need for periodic insulation-testing depends upon many factors, and diminishes with increasing adequacy of protective safeguards." This statement rather implies that bakelite paper insulation maintains its original electric strength. Does this form of insulation deteriorate with age? Do the authors as a safeguard index all e.h.t. bushings and test for dielectric and power factor before shop assembly? Have such tests been checked on site after, say, 5 years?

One can expect trouble with a layout such as that shown in Fig. 5. Separate switch-houses ought to have justified an oil circuit-breaker at each end of each cable connection between them, together with overlap leakage protection.

Turning to page 457, I am not in favour of Merz–Price protection for power transformers, as fundamentally the interlinked magnetic circuit does not necessarily ensure facsimile conditions in the protective transformers, such as would occur in the case of alternator protection. I regret that no mention is made in the paper of supplementary protective devices such as the Buchholz and Hackbridge systems, either of which makes an excellent combination with the restricted earth-leakage scheme.

It would be better if more details of the lock-out circuit were given in Fig. 12. I gather that the Dualock system would always be recommended for a new job, whereas the Time-lock system (Fig. 13) is an effort to protect existing gear. It would need applying with great caution. For example, the existing current transformers might be shown to be badly out of balance by a time short-circuit test, and would not be stable. To apply such a scheme, all the current transformers would probably have to be replaced.

The horizontal rotary movement of the oil circuit-breaker shown in Fig. 17 is many years old, but it is interesting to note the improved performance obtained by the introduction of the turbulator contact. The performance of this arrangement in its original form was based on the relatively small inertia of the moving member, the ease of fitting ball and roller bearings to reduce friction in the mechanism, and the easy cleavage of the oil. With the design of Fig. 17 the reduction in oil content applies only to the higher transmission voltages. For distribution voltages the oil content is greater than in the conventional vertical 2-break switch.

Turning to page 469, I gather that the pneumatic closing and tripping mechanism will supersede the solenoid type for lower-voltage breakers of high short-circuit rating. Is greater speed of operation the only advantage?

I think the paper is rather incomplete without test-results relating to the breaker shown in Fig. 19.

In conclusion, it is a matter of regret that a paper on a subject of such vital and national importance should be left for a single manufacturer to present. It was worthy of concentrated efforts by other leading manufacturers conjointly with similar papers by supply authorities. Such an organized presentation would have prevented too much localized design, as is perhaps unavoidable in a single paper.

Mr. B. C. Bayley: I hope that the various safeguards outlined in this paper are receiving careful study from supply engineers.

I should like to stress the necessity on the part of the supply authorities of planning their supply systems, making use of suitable switching-sectionalization and other means, so that the short-circuit current at the consumers' terminals shall not attain values that are uneconomical to the consumer. For it must be appreciated that the industrial consumer is being called upon to meet the cost of installing expensive equipment in order that he may protect himself against a condition over which he has no control, and which has, in fact, been forced upon him. While it may be argued that the interconnecting grid system assures him of an uninterrupted service, this paper reveals so many likely sources of trouble which would involve interruptions that it is a question whether it would not be safer to generate by private plant, instead of using this as a standby as we do at present.

The building of short-circuit testing stations has provided purchasers of switchgear and other apparatus with definite data where only a few years ago reliance had to be placed upon guesswork. Thus we are now able to make calculations of the conditions prevailing throughout the l.t. system and up to the consuming-plant terminals.

I am inclined to think that the anxiety to ensure that switchgear problems are solved rather overshadows cable problems, which are deserving of more attention than they usually receive.

The authors' reference to routine safeguards (page 451) stresses the fact that site testing must take second place to the more important question of the initial provision of insulation, proved by testing in the various stages of manufacture.

Mr. T. Rowland: I note that it is suggested that the carrying capacity of cables should be fixed in relation to the fault currents they may be called upon to carry; but surely the right procedure would be to limit the fault current to a value within the safe capacity of the cable.

An ideal system would presumably be one in which the

protection was so designed that any fault arising would not cause an interruption of supply to any consumer other than the one on whose installation the fault occurred. The nearest approach to this with which I am acquainted is the grid, the protective system of which appears to work very well.

Our works happen to be situated at a junction of three areas of the grid, and though a number of faults have from time to time occurred, in some cases on the lines connected to our substation, the protective system has operated, isolating the faulty section with nothing more serious than a momentary voltage disturbance. I therefore consider that Mr. Bayley need not feel seriously perturbed as to the reliability of his supply.

In regard to routine testing, I should be glad if the authors would state whether the power-factor test is intended to be applied to cables as well as to individual pieces of switchgear, as it seems to me that the incipient defective portion of cable would be so small relative to the total amount of insulation that it would produce little or no effect on the test.

I note the authors' use of compressed air to operate the circuit-breaker so as to increase the speed of operation, and I wish air had also been found to be a suitable medium for blowing out the arc. It would be a tremendous advantage if research chemists could produce a non-inflammable inert insulating liquid to be used in place of oil. The worst switchgear troubles appear to be due to the presence of large quantities of oil, which serve to feed an incipient fire.

As regards fire protection, does the CO_2 apparatus come up to expectations when it is put to practical use? I should be glad if the authors would give an expression of opinion as to the relative merits of CO_2 and ethyl bromide for fire-prevention.

[The authors' reply to this discussion will be published later.]

DISCUSSION AT A MEETING ARRANGED BY THE CALCUTTA COMMITTEE, 18TH FEBRUARY, 1938

Mr. M. Datta: To be effective and sound, safeguards against interruption of supply should depend not only on the efficient design and manufacture of protective gear but also upon careful maintenance by the supply authorities. Amongst routine safeguards, over-voltage routine testing of insulation has been condemned, but the importance of power-factor testing at site is emphasized. That this is the best single test which will indicate the condition of material without over-stressing it has now been well established. Difficulties arise, however, in its measurement.

Capacitance due to extraneous objects has been known to introduce errors into the measurement, with the result that not only are values shown which are too small, but also for good insulating material negative values of power factor have sometimes been obtained. It is therefore not understood how the authors propose to obtain accurate results from tests of individual parts of insulation unless provision be made to nullify the effect of stray capacitances due to their proximity to the test object.

Further, the curve indicating the variation of power factor with voltage of a material would be more useful than the absolute value of the power factor. It may be pointed out in this connection that insulating material like porcelain (standard mass) is held in high repute for high-voltage operation in spite of its high value of power factor and corresponding increased loss with temperature (of the order of 3 % per degree C.), since the power factor is independent of voltage. So, in order that a power-factor test may be of service, either the results of periodic tests must be analysed or the effect of power factor with increasing voltage must be studied. I shall be pleased to know whether my ideas are correct and, if so, to what extent.

Finally, I should like to state that power-factor testing is being systematically applied in the manufacture of high-voltage cables and high-tension switchgear, but in the manufacture of porcelain insulators the power-factor test is not carried out to that extent. Moreover, it is contended by some authorities that with ceramic bodies at normal temperature a low dielectric loss does not mean a high disruptive strength, so the importance of over-voltage tests cannot be ignored altogether.

[The authors' reply to this discussion will be published later.]

DUNDEE SUB-CENTRE, AT DUNDEE, 10TH MARCH, 1938

Mr. A. A. B. Martin: I would suggest that a true perspective of the subject of safeguards must omit no aspect, and must therefore give due weight to all those miscellaneous troubles which are too diverse to be anticipated and provided for. These flourish most where complicated apparatus is found, and are in a considerable measure due to that complication. To suggest that a striving to maintain or increase the simplicity of all apparatus—where progress can achieve it without loss of efficiency—is the remedy, is to name a very indirect safeguard, but one which, for a group constituting so high a percentage of all troubles, and in view of the difficulty of applying any direct safeguard, is still very important.

The general addition of busbar-zone protection would probably mean considerably increased complication. Can the authors give some idea of the frequency of occurrence of (i) dangerous and (ii) minor busbar-zone faults; and do they themselves think the time is now ripe for the general application of busbar-zone protection in this country?

They recommend automatic reclosing for circuit-breakers controlling overhead lines of voltages other than those at which protection is possible by means of arc-

suppression devices. In this country the higher-voltage lines are almost always part of some duplication of the supply system, and consequently there is small risk if one line, tripped out by a flashover, should have to await manual reclosing. Will the authors indicate more particularly the circumstances they have in mind where automatic reclosing of circuit-breakers should be adopted?

Mr. T. A. Long: The authors refer to the breaking and making capacity of the switchgear in terms of kVA, whereas I understand that B.S.S. No. 116—1937 recommends that switchgear ratings should be based on the currents and that kVA be now used only as a subsidiary form of rating. Furthermore, does not B.S.S. No. 116—1937 recommend that circuit-breakers rated at 10 000 amperes and above, or 150 mVA, should be power-closed from a distance? The authors seem to favour automatic reclosing, but they do not indicate that it is the recommended practice and may soon become obligatory.

It would be interesting also to learn the authors' experience of the efficacy of Petersen coils as a means of protection. Within my own experience the Petersen coil appears to be very effective, but the amount of relevant operating experience which has been published is very meagre.

The part of the paper which interests me mostly, however, is the use of high-speed arc-gaps as a means of protection against lightning surges. Although the authors' demonstration was very interesting, I think it will be unconvincing to those engineers who have studied surge phenomena. The fact that there is no relation between the 50-cycle flashover and the surge flashover of a needle-gap and a sphere-gap, and that a sphere-gap will flash-over under an impulse voltage before a needle-gap of the same setting, was established by F. W. Peek (Jun.)* as early as 1920. The surge impulse flashover of a line string insulator or transformer bushing does not follow the same principles, as may easily be seen by a comparison of the impulse ratios of different insulators and bushings. The results obtained by the demonstration are those one would naturally expect from the known data, but it by no means follows that proper line co-ordination on a surge impulse basis could be obtained in the way suggested by the authors.

I notice that they dismiss the effectiveness of the surge absorber in a few casual sentences, which do it considerably less than justice.

Mr. I. D. Campbell: Before busbar protection becomes as commonly accepted as feeder protection we should consider why it is necessary. The busbar zone exists in the relatively safe and uniform conditions of the switch house, and if 100 % reliability is not obtainable the materials and methods of insulation must be largely to blame. I would suggest that there is commonly too small a margin of safety below the limit of proportionality of dielectric loss. Experience also shows that a large proportion of such insulation failures as do occur in switchgear are due to the extensive use, or misuse, of synthetic resin laminated-paper products. Can the authors suggest a satisfactory way of specifying an acceptance test of dielectric loss?

If we must have busbar zone protection, it seems incredible that reliability is to be found in the balancing together of a multitude of current transformers. The frame fault-current is a good starting-point, but by itself may lead to false operation. It is reasonably certain that a frame fault-current will return via the neutral earth connection, and in stations where the neutral earthing arrangements are simple these two currents might be made to co-operate.

The relay in Fig. 6 seems to have much to recommend it and I should be interested to know to what extent it is in actual use.

[The authors' reply to this discussion will be published later.]

* "Dielectric Phenomena in High Voltage Engineering." (McGraw-Hill, 3rd ed., 1929.)

DISCUSSION ON
"MODERN FACTORS AFFECTING ELECTRICITY COSTS AND CHARGES"*

EAST MIDLAND SUB-CENTRE, AT NOTTINGHAM, 26TH OCTOBER, 1937

Mr. J. P. Tucker: I am relieved to find that the electricity costs and charges at Loughborough are much lower than the averages given in the paper for Loughborough's grouping, and in fact better than the figures for most of the undertakings falling in the larger groups. This is indicated by the figures for Loughborough given in Table L (the column numbers refer to the author's Table 2).

Table L

Years ended 31st March	Columns			
	7	8	9	10
	pence	pence	units	£
1934	1·05	1·16	1 182	5·2
1935	1·13	1·08	1 078	5·1
1936	1·16	0·96	1 101	5·4
1937	1·18	0·956	1 088	5·3

When I first read the paper I thought it was pessimistic and that it almost charged the industry with decadence. But I recollected that the industry had in 1936 attained the greatest increase of output ever recorded, and I found evidence that on a world basis our progress was quite double the average. On reading the paper a second time I concluded that it had been produced to prevent our becoming complacent.

A dominant theme in the paper is that industrial load is being subsidized by domestic load, and while this may be true the author does not produce an unchallengeable proof. In the specific case of Loughborough, domestic load certainly does *not* subsidize industrial load, as can be proved from the figures quoted in Table L. The author must surely agree that the distribution, office, mains, maintenance, and accountancy costs are lower for industrial consumers.

I am not convinced that the load factor of the total domestic demand is in the future going to compare favourably with the industrial load factor, unless there is a big reduction in working hours.

We must admit that many tariffs would appear unsound when considered on a "producing and selling" basis (if such is possible). But is it not just as true to say they are sound on the principle that we charge what we can get? We can get 4d. per unit and more for a large percentage of our lighting load, but little water-heating can be obtained where electricity exceeds ½d. per unit. It is a question of getting what we can, provided we don't lose money on the transaction.

I should like to argue against the "fixed-consumer-charge" method advocated by the author. It is quite as unsound as many of the other tariffs already in successful operation and, unlike the established forms of tariffs, it is void of equity. Why should the same fixed charge apply to an artisan's home where there are many consumers to each 100 yards of distribution as to the large house in a "residential" district where distribution costs per consumer are much greater—sometimes in the ratio of 6 : 1? If the scale in Table 15 were applied to Loughborough almost every domestic consumer would pay more, and Table 16 makes the case for the Loughborough consumers even worse.

In my opinion "units per £ of distribution capital" means nothing. Surely it is the "active" capital which matters. The carrying-forward of capital already repaid must—as the years go by—show an increasingly depressing but untruthful picture.

That the average figure of units per consumer for the whole of this country is decreasing, is abundantly proved in the paper. The figure for Loughborough is also diminishing but in a less degree, and I have sufficient optimism to think that an upward trend is coming.

While I agree that a paper of this nature can only be useful if it is comprehensive, I think that groups of the most progressive undertakings should have been selected in addition, in order to show what can be done. To avoid the charge of invidious selection, the names of the selected undertakings could have been withheld.

Items 1 and 2 in Table 4 are difficult to understand, and in any case a consumption of 900 units per annum for a fully equipped house seems absurdly low: in Loughborough we have many prepayment consumers using over 3 000 units per annum.

Mr. M. Wadeson: The author's main point is that with increasing numbers of domestic consumers there has been a decline in average consumption. He gives as a primary reason for this the connection during recent years of large numbers of the smaller class of houses. It is agreed generally that this class of consumer has a small consumption only at the outset, but I can find no evidence that he will not subsequently increase his annual consumption.

Of the 6·6 million domestic consumers quoted for 1935–36 in col. 9 of Table 1, I find that less than 10 % have cookers, only 2·9 % have water-heaters, and under 2 % wash-boilers. From these figures it must be concluded that the use of electricity in private houses for

* Paper by Mr. J. A. Sumner (see vol. 81, p. 429).

purposes other than lighting is confined to a narrow section of the whole population. The middle classes generally have not replaced any of their existing heating and cooking appliances. Under these circumstances, if an increase in consumption is to be obtained, we must encourage those people who have not yet considered the use of electricity for these purposes to adopt electrical appliances when they replace their existing apparatus.

I do not agree with the author that the present two-part tariffs for private houses are too scientific. I find that the two-part tariffs most generally in use, in which the standing charge is based on rateable value or floor area, are by no means scientific but purely rule-of-thumb.

Since the largest part of domestic supplies are lighting units, supplied at a comparatively high flat-rate charge, it can be legitimately claimed that they subsidize to some extent the power tariffs.

In increasing the consumption of the smaller class of consumer, apart from the question of a standard tariff there is the greater difficulty of collecting the annual sum for a full supply of electricity. This class of consumer is accustomed to pay on a weekly basis, and without some special means for the weekly collection of the fixed charge I cannot see how these customers are to be given the advantage of the low unit rate.

Mr. S. C. Ginno: I am surprised to find that, according to the author's statement, relatively little progress has been made, especially in the domestic application of electricity. I do not think that recognition is given in the paper to the extensive development which has taken place in the areas of progressive undertakings. The results of this may be found in the growth of assisted wiring, which, whilst it has the effect of increasing the number of consumers, also lowers appreciably the number of units used per domestic consumer. In Leicester, the effect of connecting some 17 000 assisted-wiring consumers was to reduce the units per domestic consumer from 825 in 1931 to 530 in 1934: the present-day figure is of the order of 1 000. Such development cannot be termed unprogressive, although the figures seem to indicate such a state of affairs. Assisted-wiring development does not begin to make itself felt until the installation has been paid for, when the consumer will, if satisfied, commence to use the supply for purposes other than lighting. The net result is that consumption figures are misleading during a period of development, and can only be reviewed in their true perspective upon completion of such work.

The second point I should like to make concerns intensive development, or how to increase the units taken by a given consumer or installation. This is the most difficult of our tasks and one which will test the ability of our sales staffs, irrespective of the price per unit. Development having in the past year reached a point within 10 % of the maximum possible (with most supply undertakings), we should now begin to see a steady increase in the units used per consumer. Such an increase is noticeable in Leicester and, I expect, also in other towns.

A great deal still remains to be done, however, in providing more efficient sales staffs; the removal either by hire or by hire-purchase of that retarding influence, high-cost apparatus; and lastly, prompt and alive service.

Contrary to the opinion of the author, I am sure that uniformity of tariffs, by itself, will not produce progress. The form of tariff, or method of charging, is actually of little interest to the consumer, who is more concerned with the total cost of the service provided. Progressive development can only result from good management and successful selling.

Mr. T. Rowland: With reference to Table 7 and the suggestion that power users have been subsidized by the domestic consumers, this is a very popular cry in certain districts. The author appears to have fallen into the error of assuming that the average power user is an average consumer, i.e. average as to number of units consumed, load factor, etc.; he also seems to me to have over-estimated the number of power users.

The undertaking with which I am connected has 113 power consumers out of a total of 12 460, representing rather under 1 % of the total number of consumers, and not 13 % to 18 % as indicated in Table 1. Further, in our case the 113 power consumers take over 26 million units out of a total of 37·64 million units taken by the whole 12 460 consumers, the average consumption of a power user being over 230 000 units per annum as compared with the average for all other consumers of 925 units per annum. I therefore fail to see how the author can justifiably assume that the average power user is an average consumer as to size, load factor, etc. It seems that the argument, based on Table 7, that power users as a class are being subsidized by the domestic consumers, is erected on insecure and unreliable foundations.

Turning to page 451, we see that under the suggested new tariff each power consumer would have to pay a fixed annual charge of £24·4, which is a very small sum for an average consumer with a consumption of the order of a quarter of a million units per annum, and a quite negligible one for the large consumer taking, say, 15 million units per annum. If this tariff were adopted for our undertaking there would be a very large reduction in income, as both the power and the domestic users would get a large reduction in the price of energy and the undertaking would be run at a considerable loss.

Referring to domestic consumption, the author states that where the price is high the consumption is low, and vice versa, but I think it is rather erroneous to assume that this is always the case. If the tariff is rightly drawn up, then where the consumption is low the all-in price per unit will be high, and likewise where the consumption is high the price will be low.

I am interested in the figure given for the consumption in the author's house—13 000 units per annum. I estimate that in our area the price would average out at 0·66d. per unit. As a comparison I would mention a consumer of ours who uses just under 20 000 units per annum, in a house with a rateable value of £68 per annum, the all-in average price per unit being 0·554d. A consumer with a somewhat larger house, using 10 700 units per annum, pays an all-in price of 0·65d. per unit; a smaller one, consuming 7 050 units per annum, 0·581d.; and a still smaller one, in a working-class district, with a consumption of 2 800 units per annum, an all-in price of 0·683d. per unit. The tariff adopted by these consumers is available for all domestic users, yet the average consumption of domestic users for the past year was only

630 units and the average price 1·592d. per unit. The author would presumably say that the consumption is low because the price is high, but the above examples show that this is not the explanation.

I feel that the cost of the installation of apparatus is the obstacle that has to be overcome. The man who rents a house finds that it is equipped—in some fashion, at any rate—with all the essential accessories to meet his needs. There will be a cooking range of some kind, a domestic hot-water supply, a fire grate or two, and, almost certainly, electric light. To obtain increased consumption we have to induce him to incur the outlay for electrical apparatus to displace his existing appliances, and the process will naturally take some time. I think, however, that the instances I have quoted show that an annual consumption of 2 000 units per consumer is a very reasonable figure to expect from domestic consumers.

Mr. A. Brookes: The author states that the cost of distribution will at least be maintained and will very probably increase over the next few years. This is very doubtful, because the question of the increase in material costs will only have a limited influence and, in my opinion, the question will be swayed by the distribution density. During the last few years the tendency has been for towns to extend outwards away from the centre of generation. This trend will reach a limit, and since the new houses are mainly of the type that give us a lighting load only, with relatively small possibility of expansion per householder, then as distribution cables are completed there will more probably be an increase in loads taken nearer the generation centre, as cooking loads are more general here. This factor will have a marked influence on distribution costs.

Mr. B. C. Bayley (*communicated*): The author suggests that the cost of generation must increase with the rising cost of coal, and that distribution costs in the near future may rise owing to the higher cost of copper, although this may be neutralized by increased density of load. These factors point towards the probability that the consumer will have to foot the bill.

It is also suggested by the author that the domestic consumer subsidizes the industrial power consumer. This may be true in some cases, for the supply authority is compelled to consider, in arriving at the tariff, what are the conditions under which the consumer can generate with private plant. Take the case of an engineer to a large industrial organization which owns a stand-by Diesel generating plant and is faced with large extensions. It is for him to find out whether the supply authority can provide the energy required as cheaply as he can generate it. It is admitted that Diesel oil-engine plant is the most economical form of generation in comparatively small stations, as generating costs are well below 1d. per unit. There is, however, another factor in favour of private plant, and that is that it involves much less outlay on the consumer's e.h.t. and l.t. distribution switchgear than if he takes a supply from the authority. Now that the large supply undertakings are interconnected with the grid, and the capacity of the stations has enormously increased, it is necessary to install switchgear of sufficiently high rupturing-capacity to handle safely the heavy short-circuit currents which are inseparable from such large systems of supply. These considerations tend to keep the charge for electricity for industrial power at an economical figure. How will this figure compare with the supply authorities' actual total cost of generation and distribution?

[The author's reply to this discussion will be found on page 510.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 2ND NOVEMBER, 1937

Mr. O. Howarth: The author appears to contend that if the price is low enough, domestic consumption will rise above the average of 2 000 units per consumer per annum, and he sets out to show this is so by his collection of data.

On page 444, referring to Table 9, he says " the slight increase in the total cost of distribution in 1925–26 is associated with a reduction in the units sold per £ for 1925–26 and 1926–27; a similar increase in 1930–32 resulted in a corresponding decrease. . . ." The increases are, however, so small that I do not think he is justified in his conclusions. The capital charges alone amount to more than 50 % of the total cost of distribution, and in these circumstances it is inevitable that the units sold per £ of distribution cost will go down.

I should like the author to explain Table 7. In cols. 5 and 6 he gives the surplus expressed as a contribution to the total cost of distribution—in col. 5 by power supplies and in col. 6 by domestic supplies. Adding them for 1934–35, they total 91 %. Who pays the other 9 %? The accuracy of his data depends upon having a uniform basis on which the figures are supplied by the various undertakers, and anyone who has had experience of the collection of such information by supply undertakings will not be prepared to attach much weight to small variations in them. For example, for each cooker installed some undertakers add 6 kW to the " kilowatts connected " figure and others 1 kW.

The author does not accurately segregate the costs for domestic and power supplies. Probably most power consumers in this country are fed from the high-voltage system and have their own substations, whereas the domestic consumers are fed from the low-voltage network. He mentions the paper by Messrs. Woodward and Carne* in which it is clearly shown that the cost of supply per kilowatt of demand on the low-voltage system, making due allowance for the time at which the demand occurs—i.e. the consumer diversity—is considerably greater, owing to the cost of providing the low-voltage network, than the cost per kilowatt of supplying a high-voltage consumer. Quite a large proportion of the capital expenditure necessary to supply a domestic consumer is incurred on the low-voltage network, and it therefore does not seem reasonable to take the whole of the supply industry in this country and lump the costs of the high- and low-voltage networks together, as the author has done. It is like mixing wholesale and retail figures for any particular business.

Fig. 6 shows that whilst the percentage of capital invested in generation has gone down, the percentage of

* *Journal I.E.E.*, 1932, vol. 71, p. 852.

capital invested in distribution has gone up. I should like to know whether the C.E.B. system is treated as a generation or as a distribution charge in this paper. Part of the distribution increase is the result of spending money in order to improve the efficiency of generation by building larger power stations more remote from the load, and transmitting to the area of supply. Obviously, money has been put into distribution in order to save a greater sum on generation.

The author shows by his curves that most domestic units are sold where the price is lowest. I suggest that as the great majority of consumers have a 2-part tariff available the fact of the matter is that the price is lower because more is used.

Table 5 shows that the load factors of domestic supplies are quite good and that rather better figures are obtained in industrial areas. The upper part of the Table relates to six areas where there is little industrial power, the lower to six industrial areas. I do not think that any useful conclusions can be drawn from a comparison of the figures for the wealthy stockbrokers of Wimbledon with those for the colliers of Wigan. I have looked up the figures for these towns and find that Wimbledon manages to achieve an average sale of 1 270 units per consumer, and Wigan 563. There is a greater proportion of small houses in Wigan, and the average income is probably considerably less than in Wimbledon; this must have considerable influence upon the average consumption. The author does not mention that the price of electricity is only one factor in determining people's use of it in their homes: another factor is the cost of appliances. For instance, the cost of an electric cooker is at least equal to the cost of the units it consumes at ½d. per unit. If we are to get a considerably increased use of electricity amongst domestic consumers, we must have much cheaper apparatus available.

On page 438 the author mentions the E.D.A. finding that the small householder pays between 2s. 6d. and 3s. 6d. per week for lighting and heating by means other than electricity, equivalent to 1 560 units per year at 1d. per unit, or an annual sum of £6 10s. This figure, however, would not include a hot-water supply, and in this area it is customary in all houses built to-day to put in hot-water services worked from the coal fires.

I have taken the figures for two or three undertakings in this area and worked out the average cost per unit for houses using up to 12 000 units a year. The plotted points lie on or slightly below the curve given in Fig. 3; thus one might expect the annual domestic consumption in this area to average 12 000 units, but it does not.

On page 440 the author says "industries follow cheap electric power, often without regard to other features which may ultimately have an equal influence upon their cost of manufacture." Why is it that industry is moving to the London area where power is dearer than in Lancashire, and labour is dear and scarce? I suggest that it is because business men are influenced by fashion. No doubt it is quite useful to achieve uniformity, but I think it is more useful for the supply industry to concentrate on cheap domestic appliances and enable full use to be made of the already-available cheap domestic power.

Mr. W. E. Swale: The electricity supply industry of this country has made remarkable progress under conditions of relative freedom. Three out of every five homes are already wired, and the power requirements of industry can in most instances be adequately met with a public supply. The more cautious among us are inclined to leave well alone. We trust to an increasing appreciation of the ideal of public service to remove, gradually, the obvious imperfections of a system which has tended to combine the best features of public and private control. Nevertheless, in view of pending legislation, we must try to clarify our views on the matters which the author presents in his paper.

The Electricity Commissioners' returns are, at present, the only official source of data available; has the author appreciated what serious errors the use of these returns has involved? In checking over the results of the Manchester undertaking with the appropriate columns in Tables 1 and 2 of the paper, I find that Manchester follows the national trend very closely. But, turning to Fig. 1, I see a misrepresentation of fact which seriously invalidates a good proportion of the author's subsequent argument, not necessarily in the value "consumption per consumer" but in the average price per unit obtained from the "domestic" consumer. The Commissioners' returns are in this respect misleading, because they include under one heading ("lighting and domestic") all the small offices, shops, professional residences, etc., where the bulk of the consumption is taken at the high flat rates for lighting. In Manchester in 1936–37 the consumer classification was as follows:—

Private residences	120 428	(79 %)
Professional residences	632	
Shops and offices, and warehouses	27 939	(18 %)
Power users	4 829	(3 %)
	153 828	

If, as the author has done, we group 97 % of the consumers together, we find an average consumption per annum of 825 units (approximating very closely to the national average) and an average revenue of 1·992d. per unit. But this latter figure is more than twice the revenue actually obtained from the purely domestic consumer. If the Electricity Commissioners could be persuaded to publish, in future returns, the figures for domestic consumers alone, the author would be able to present one of his arguments in truer perspective.

The decrease in consumption of the pure domestic consumer, and particularly of the "all-in" consumer, is of course a characteristic of recent development in many parts of the country. But I consider that the author attaches undue importance to the price-per-unit factor alone, and overrates the "elasticity" of the demand, or the "value" of electricity to the consumer in relation to other desirable commodities or services. Many domestic consumers choose to spend their money on motor-cars, radio sets, cosmetics, or even electric refrigerators (the latter distinctly less desirable from our point of view than a combination of cooker, wash-boiler, and water-heater, which can be hired at about one-third the quarterly charge); but if they become "hard up" for such reasons I do not conceive it the business of the electricity supply authority to cut its prices in order to be directly competitive with the cheapest of the alternative services.

In most parts of Lancashire there is already such a uniformity in methods of charge for domestic supplies that I attach little importance to the author's reason No. 3 as a factor in retarding development.

Coming now to his second main argument, that present power charges are too low, I am much more nearly in agreement with him, though I suggest that his findings are subject to many qualifications. Thus his generalization (page 440) that "industries follow cheap electric power" is, except in very exceptional circumstances, incorrect. Lancashire, on the average, has lower power charges than any other area in the country. Yet new industries have congregated around London, where power charges are generally far higher, and new load has been lost to private plant.

Table 5, illustrating the high load factor of the domestic load, is a very good point with which to support the author's argument, but he does not mention one important distinction between the power load and the domestic load. With the former, the undertaking's responsibilities end at the meters! It is beyond the meters, with the domestic consumer, that our real responsibilities begin. The cost of supplying the domestic consumer is therefore appreciably higher than a plain generation-cum-distribution analysis reveals.

I am in complete agreement with the view that tariffs for small power users are unjustifiably low, and I should welcome any move to check still further reductions. But as regards large power users, a class which in industrial areas may represent up to 50 % of the total load, the issue is not quite so clear-cut as the author would have us believe. He has, as I know, wide experience in analysing the costs of private power generation; yet he admits that there may be "special cases" where his generalizations do not hold good. I suggest that had he been stationed for any length of time in the home of the steam engine (and to some extent of the steam turbine), and had he had an intimate experience of the early difficulties of our supply undertakings, or of the conditions prevailing in cotton mills, woollen mills, chemical works, and collieries of this area, he would not have been so dogmatic regarding the price at which new power load can be obtained, or existing load retained. The statement on page 440 regarding the "policy of bargaining with an undertaking for lower prices" may be open to misunderstanding. If the author intends to convey the impression that such bargaining achieves its object to any appreciable extent I think he does less than justice to the business acumen of electricity supply executives.

I should particularly like to have his opinion regarding the value of the industrial electric heating load, which he does not mention, but which is now being developed to quite an appreciable aggregate. On the average, the marginal value of electric heating in industry is lower than in the household, a fact our competitors appreciate fully. Does the author think we should neglect the greater part of this potential load; or should we make use of it, to the fullest extent, in increasing the diversity of the power load? Substantial progress in this direction is only being made in areas enjoying cheap power tariffs.

The author's suggestion for a national domestic tariff based on an averaged (not necessarily uniform) "consumer charge" is certainly bold, and might overcome many of our minor difficulties. He makes a strong case for the economic justification of his scheme, but I suggest that there are many facts which he has not ascertained and many factors which he has not assessed correctly. The North-West England and North Wales Area of the C.E.B. would form an ideal territory for further detailed investigation. It contains a huge population, every type of load, and every stage of electrical development.

Mr. L. Romero: In Table 1 the author classes as domestic consumers all except industrial power consumers, and as domestic units all units sold for lighting, heating, and cooking (including an unknown quantity of units sold to industrial power consumers for lighting and heating), and also all units sold to shops, offices, hotels, theatres, public buildings, etc. That is to say, the whole basis of his statistics is inaccurate to an unknown, but certainly very large, extent. This is particularly true of the figures for average revenue per unit sold, as the inclusion of non-domestic lighting units must have the effect of making these figures much higher than they would be for domestic supplies alone.

The figures given in col. 10 of Table 1, purporting to show the average domestic consumption per consumer per annum for a number of years, are most inaccurate as they are arrived at by dividing the units sold to all consumers for everything except industrial power by the number of purely domestic consumers. This procedure gives results which may easily be 100 % above the true average domestic consumption: a similar criticism applies to Table 2. In cols. 7 and 9 of Table 2 the contradictions of the author's law that sales vary inversely as the average revenue obtained per unit are so many and so considerable as to require some explanation. I do not know why the consumers in Group 17 should consume on the average 991 units per annum at 2·1d. per unit while the consumers in Group 18 only consume 868 units, although their price is 10 % lower, i.e. 1·9d.; but I suspect that it is because Group 18 contains a larger percentage of industrial towns, and therefore of consumers of the poorest class. Another cause contributing to these discrepancies is the inclusion in the domestic figures of all units except industrial power. The author's arbitrary division of total consumers into 90 % domestic and 10 % power for undertakings over 5 million units seems to me very far from the mark. In Salford, an industrial city, the percentages are about $1\frac{1}{3}$ % industrial power and $98\frac{2}{3}$ % other consumers.

The author seems to think that domestic consumers (the great majority of whom are poor) are merely waiting for an attractive tariff to make them use thousands of units per annum. Attractive domestic tariffs as low as, or lower than, that suggested by the author are already in operation in a large number of undertakings in this country. Under these tariffs any domestic consumer can obtain his whole supply at about 0·6d. per unit merely by cooking his food and heating his water by electricity and/or by making some use of electric fires. It will be seen, therefore, that a very low price is available for a large proportion of the population of this country.

The reason why the average consumption per domestic consumer has gone down during the past 5 years is of course that consumers of the poorest class, whose actual and potential consumptions are very much lower than

those of the comfortable classes, have been connected in enormous numbers during that time. The building-up of a high average consumption by the poor consumer will take time, and all the inducements—in the way of low tariffs and hiring facilities—which we can offer.

In Salford 96 % of our domestic consumers are on the all-in tariff. During the past 5 years the number of domestic consumers has increased from approximately 13 000 to 39 000, and their annual consumption from 8·9 to 24·7 million units. This means a small decrease in average consumption per domestic consumer, from 685 to 633 units. During the previous 5 years, when we were connecting relatively few consumers of the poorest classes, the number of domestic consumers increased from approximately 6 500 to 13 000, and their annual consumption from 2·5 millions to 8·9 millions, showing an increase in the average consumption from 385 to 685 units per consumer. During the immediate past 5 years the average consumption of all classes of domestic consumers has continued to increase steadily, and the only reason why the average domestic consumption as a whole has decreased from 685 to 633 units is that the ratio of low-income to comfortable-income consumers has enormously increased.

On page 444 the author recommends as the final goal a national 2-part tariff with a fixed annual charge common to and equal for all consumers, with no regard for the nature or amount of their demand, and also, I gather, a universal unit charge of about ½d. This proposal ignores completely all the factors producing differences in the cost of supply between one consumer and another except number of units. It ignores completely the difference in standing cost between supplying a consumer with a maximum demand of 2 000 kW and a consumer with a maximum demand of 1 kW. It also completely ignores load factor and the time at which a supply is used in relation to peak load. If an attempt were made to introduce such a tariff the effect on electrical development would be disastrous.

I am surprised to see in Fig. 1 that the undertaking with the lowest price (just over 1d. per unit) has the average annual consumption per domestic consumer of about 400 units, whereas the undertaking with the largest average consumption per consumer, nearly 3 000, sells at an average price of 2·35d. What are we to make of statistics such as these?

On page 431 the author gives figures for changes in the number of domestic consumers and in average consumption for a large undertaking over the last 10 years. I do not think these figures can be taken as typical, because I find that during the same period the number of domestic consumers in Salford has increased by 500 % and the average consumption per consumer by 64 %, as against the 30 % decrease given by the author.

Mr. S. R. Mellonie: Referring to Table 1, the increase in domestic units shown in col. 2 represents no less than 320 % in something under 10 years; in these circumstances there is no justification for the author's rather doleful view of the progress made. As a measure of efficiency, the figure of units sold per £ of capital invested in distribution is open to several objections. In the first place, it invites inquiries as to the nature of the service rendered; for example, if the regulation is poor, difficulty may be expected in the development of cooking load. Another factor is that inadequate stand-by plant will involve interruptions to the supply for maintenance work. The point I desire to make is this: an undertaking for which the units sold per £ of distribution capital are well below the maximum figure can yet be rendering a better service to its consumers than the "most efficient" judged by such a yardstick.

Mr. C. C. Kirby: Cheaper electricity is not sufficient to ensure increasing sales, and I say that particularly because I have in mind an undertaking where there is a remarkable output of cookers, and yet the average price charged per unit is higher than that obtaining in many undertakings in Lancashire.

I have obtained certain figures for the undertaking for which I am responsible, on a similar basis to those contained in the paper. I have chosen the 5-year period from 1933 to 1937 in order to obtain a fair idea of the trend of future development. I find that the units sold per £ of distribution capital have risen from 14·5 in 1933 to 28·1 for 1937, and the units sold for domestic purposes per consumer have increased from 740 to 1 120. During the same period the average price obtained per unit has dropped from 3·44d. to 1·91d.

Mr. A. W. Crompton: The price chargeable for railway supplies has to be determined in accordance with the Electricity (Supply) Act, 1926 (Section 12), as amended by the Act of 1935 (Section 3) on the basis of cost to the undertaking concerned, but it is questionable whether if the same principle were applied to tariffs for domestic supplies there would be any appreciable reduction in the charges to domestic consumers in this area. The tariffs charged by an undertaking are revised from time to time by having regard to the existing and prospective revenue from the various types of consumers and to considerations of future capital outlay and annual charges; but if, as the author suggests, an overriding authority is to have statutory powers to decide what tariff shall be charged for domestic supplies such procedure may have the effect of retarding rather than accelerating development.

Mr. W. Fennell: The policy of the uniform tariff for domestic purposes might easily be disastrous to the electricity supply industry so far as its domestic consumers are concerned. The uniform price would obviously in some places be above and in others below the value of competing services. At present, if an area is of moderate size, and a certain desired type of load cannot be obtained or retained on the existing tariff, one can easily alter the tariff. With a very large area, however, this policy would involve a reduction over an unnecessarily large number of consumers, to the detriment of revenue. Alternatively, the non-competitive price would be maintained and business lost to the competitive service. Let me illustrate my point by explaining what happened in a town where the local authority of which I was engineer supplied electricity, but the neighbouring (Birmingham) Corporation supplied gas. The Birmingham Gas Department were before the War supplying high-pressure gas lamps in certain streets in that city at a uniform charge of £5 per annum per lamp, including gas, cleaning, and maintenance. Our electricity consumers had to use three or four arc lamps in series to

obtain reasonable economy, but small shops did not want more than one lamp. One day I found that the Birmingham Gas Department were laying high-pressure gas mains down the principal streets of the town and were beginning to get orders locally at £5 per annum per lamp. To meet this serious competition we laid immediately a 3-wire 100-volt d.c. main in the shopping streets and offered one or more magazine arc lamps, which would burn 60 or 70 hours with one trimming, at £4 17s. 6d. per lamp, including cleaning. In a very short time we had 40 such lamps installed, and the Birmingham Corporation had 5 lamps only! The reason for our success was that the Birmingham Corporation could not come down to £4 17s. 6d. in our area without upsetting hundreds of consumers in their own city.

It is obvious that the "idea" of a uniform price for electricity over a very large area should be dropped, so long as our competitors have small and isolated areas, and could use that fact to defeat us in detail.

[The author's reply to this discussion will be found on page 510.]

WESTERN CENTRE, AT BRISTOL, 8TH NOVEMBER, 1937

Mr. J. Fradsall Smith: The author assumes a constant or even declining consumption per domestic consumer and deduces that something is wrong with electricity distribution in this country. As a contributory cause to this state of affairs he brings forward the obvious inference that charges for domestic electrical energy are too high and charges for industrial power are artificially low at the expense of domestic power. Tables 1 and 2 of the paper are, however, equally capable of the interpretation that industrial power supply has assisted domestic supply, and it is significant that according to Table 2 the large undertakings with the greater proportion of power obtain the lowest revenue for domestic units.

A constant or even declining domestic consumption per consumer can be equally evidence of healthy development, implying that electricity undertakings are not confining their attention to the more remunerative and more easily serviced portions of their territory; but have extended their mains and facilities so as to give supply to an increasing number of consumers whose capacity for consuming electricity is less than that of the consumers formerly served.

It is precisely in the period covered by Table 1 that public attention has been focused on electricity supply matters, and it is probably true that, as a result of the interest which has been aroused, electricity distribution authorities now operate with enthusiasm for development, instead of complacency.

Mr. G. H. Bowden: An important factor in connection with the management of a supply undertaking is the influence of price variations, which are under the control of market conditions and manufacturers' salesmanship. Many undertakings are to-day labouring under the heavy yolk of capital expenditure incurred at an inopportune time, and many engineers are striving to equal the results obtained by others where extensions have been clearly foreseen and provided in advance.

The author's comparison of domestic tariffs with power tariffs seems to me to be incorrectly based. Electricity has now become a utility which is part of the national life, and domestic and industrial use are becoming increasingly interdependent; tariffs should be considered on these lines.

Load-factor improvement in both domestic and industrial supply is the direction in which there is most hope of development. It is possible that transport limitations, as exemplified by recent efforts in the London area in regard to the "staggering" of working hours, may result in benefit to the supply industry.

The form of tariff for domestic supply should be standardized, and development work should emphasize this factor as an aid to the public's more ready acceptance of the two-part tariff. In the case of industrial loads of large magnitude the two-part tariff with power-factor clauses is the best, but business should not be lost through insistence on the undertaking's own particular method of charging, because an equally satisfactory financial return can be obtained from sales upon a stepped-unit-rate basis at the right price per unit.

The present tendency towards decentralization of industry suggests the need for a form of clearing house in regard to supply quotations. Cases concerning Fringe Orders draw attention to this need, and the author emphasizes it by his reference to the case of a water company seeking competitive quotations from neighbouring power companies.

Mr. W. Roberts: I scarcely think that the author is justified in expecting that anyone with a consumption of 600 units would obtain a financial advantage by changing over to a two-part tariff. In this district a larger consumption is called for before the change warrants consideration.

I am surprised that the average consumption by all users is still in the neighbourhood of 800 units per annum. The cost of distribution per consumer is more likely to be lowered by inducing existing consumers to use more electricity than by laying out capital on new connections. In my own house, where hot water is obtained entirely from an electric heater, the consumption is 4 000 units per annum for water heating alone. The heater provides all the hot water necessary for one bathroom, one wash-house, one sink, and four wash-basins, at a cost of just over 4s. per week.

Mr. Harold Midgley: It is obvious that the author has carried out a considerable amount of investigation, and it is unfortunate that the value of this is discounted by the assumptions made at the outset of the paper. At the same time one must sympathize with him in regard to the difficulty of obtaining the information required for such investigations, a difficulty which is increased by the varying ways in which electricity undertakings carry out their financial arrangements, e.g. the extent to which work of a capital nature is charged to revenue or to capital, or the extent to which the expense of change-over from direct current to alternating current is met from

revenue or reserve. Whilst these differences may be regrettable from the statistical point of view, freedom of choice in matters of this kind has, in the past, been very beneficial.

I cannot altogether agree with the author that the sale of electricity, measured in terms of units per head of population, is dependent only on average price. My experience has demonstrated that improvement in publicity, and the provision of hire services, have at least as great an effect in increasing consumption of electricity as reduction in tariffs. Whilst many new consumers in recent years have been only small users, it must not be overlooked that recent developments have been to a much greater degree than in former years amongst working-class dwellings. Further, the introduction of electricity supply into a house for only a limited usage is usually the thin end of the wedge towards an increased use as the benefits are realized.

It is often said that saturation from the electrical point of view is near at hand, and in fact I quite frequently heard this view expressed 15 years ago. The statement was untrue then, and surely it is equally likely to be untrue now.

Whilst the author advances very sound reasons against a possible reduction in distribution costs, as demonstrated in Fig. 5, these reasons only apply on the assumption that no substantial improvement is obtained in load factor. Any improvement in load factor will be reflected in reduction of distribution costs, which are mainly fixed charges, and this strongly emphasizes the importance of developing off-peak loads such as night water-heating and battery-vehicle charging.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT NOTTINGHAM, MANCHESTER, AND BRISTOL

Mr. J. A. Sumner (*in reply*): I should like to express my thanks to the numerous contributors to these discussions for the expression of so many views, whether critical or complimentary. If the discussions have more clearly formulated opinion with regard to the important relationship between demand and charges, the paper will have served the purpose for which it was written.

These later discussions again tend to crystallize around the question of a decreasing average national consumption. Many speakers accept this condition as being prevalent, but seem to reassure themselves by stating that the condition is a natural one and only temporary, being due to the large recent increase in the connection of small consumers. So far, therefore, they agree with the statements which I have set out in the latter part of the second paragraph of the "Summary" to the paper.

On page 434 (vol. 81), however, I have described this decreasing consumption as a condition of "mal-development," and many contributors appear to disagree with this description and with the reasons which I have advanced to account for this lack of development. They suggest that this condition of a falling average consumption with an increasing rate of connections is a healthy one because, ultimately, the new small consumers will increase their consumption. I have not been able to accept their suggestion because, as pointed out in the paper, I maintain that the new small consumers are unlikely to increase their annual consumption owing to high fixed charges and high domestic prices generally. These charges are such as to prevent a high elasticity in the domestic demand, which is shown to occur only when the average price falls below 2½d. per unit. In a recent paper entitled "Electricity Demand and Price,"* Mr. D. J. Bolton has provided a valuable economic analysis of electricity-supply demand in which he has given a definition of "elasticity of demand," and has given an appraisal of its value and consequences in electricity supply. Since his analysis appears to confirm the views which I have put forward in the paper (see his statement on page 204 that "the elasticity throughout the country is almost entirely due to the taking-on of fresh consumers, and such an elasticity is far from being the most profitable type for the undertaking"), I am encouraged to persist in the views in this connection which I have put forward in the paper.

* *Journal I.E.E.*, 1938, vol. 82, p. 185.

This general statement, and my earlier reply, directly answer some of the contributions to the discussion, and I therefore deal below with only the remaining points.

Again during these later discussions the view has been expressed that the electricity supply industry is in a satisfactory condition because of the annual increase in the amount of total consumption. But I fail to see that this growth in the rate of consumption can, of itself, indicate that conditions are satisfactory. If I may use a simile, it is rather like saying that we should be satisfied if we found that the weight or height of a child was greater in one year than in the preceding year; in such an instance we should wish to know whether the increase was greater or less than the average for other children of the same age. Unfortunately, we have no standard by which to compare the growth of electricity supply, and I can only suggest that the analyses made in the paper indicate that the growth in the consumption of electricity may be less than one would expect of an adolescent industry.

I should like to emphasize the suggestion made by Mr. Bowden in the Bristol discussion, that some form of clearing house could be established to deal with quotations by supply undertakings to large power consumers. Even if control of the quotations were not established, as occurs with certain electrical manufacturing organizations, it would be of value to obtain knowledge of the various quotations which are made for a particular inquiry, so as to ensure that the lowest tenderer obtains at least as much as his original tender price.

Manchester Discussion

In reply to Mr. Howarth re Table 9, I suggest that if the changes to which he refers are considered over the whole range of the Table the constant nature of the variation, although the change is small, justifies the conclusions which I have drawn. I agree that the proportion of capital charges in distribution is increasing, but not that it is inevitable that the number of units sold per £ should decrease, provided that tariffs and charges are suitably administered. The remaining 9 % of consump-

tion and charges which are not included in Table 7 is due to public lighting and traction supplies. The Central Electricity Board capital has been apportioned between generation and distribution in the manner stated in the earlier discussions. With regard to the question as to whether prices should and do follow increased demand, or vice versa, I would refer Mr. Howarth to the first of the three numbered paragraphs in the Summary to the paper, and particularly to Mr. Bolton's recent paper. Most of Mr. Howarth's remaining points have been dealt with in my earlier reply, but I should like to express my agreement with his view that cheaper consuming apparatus ought to be available.

Mr. Swales provides a thoughtful contribution, and I agree with the difficulty which arises when analysing conditions in the supply industry, in view of the inadequate nature of the statistics published in the Electricity Commissioners' Annual Returns. The paper will have been useful if it succeeds only in showing the need for undertakings to provide more detailed statistics. Mr. Howarth and Mr. Swales raise the point that the recent move of industry to London, where electric power charges are high, disproves my statement that " industries tend to follow cheap power." But I think that most of the new industries around London are of the type which has a relatively small power consumption. As regards power prices, I am sorry if I have conveyed the impression that electricity-supply executives are not generally alert and successful. I had intended to refer to the relatively uncoordinated bargaining powers between the various executives in electricity supply, as compared with the much more organized bargaining strength of the manufacturers (see Mr. Bowden's contribution and my reply thereto.) Industrial electric heating, of course, covers many branches, but I consider that it will be a very valuable acquisition in the near future, particularly if arrangements can be made to keep the load off the winter peak, either by increased storage capacity in some cases, or by reduction of load during peak hours in such cases as, for example, electric furnaces for steel-melting.

I have already expressed my agreement with Mr. Romero's criticism that it would be better if the consumption of shops, etc., could be separated from purely domestic consumption. I also agree that, if this could be done, the true figure of average domestic consumption would not only be very much lower than I have stated but would probably show a much greater rate of annual decrement. There are, of course, a large number of causes which require investigation in order to explain the variations in col. 7 and 9 of Table 2, but, although I do not rely upon Table 2 to prove the inverse law to which Mr. Romero refers, I think that Table 2 can be used to support my case. If the ratio of power to domestic consumers is less than 1 to 10, the average domestic consumption in col. 10 of Table 1, referred to above, will be depressed even more. The characteristics of the domestic supply in Salford appear to be very similar to those of Hull and Sunderland, to which I have referred in the earlier discussion. Fig. 1 is, of course, a graphical representation of a large number of facts published in the Electricity Commissioners' Annual Returns, and relates to approximately 600 supply undertakings. The two points to which Mr. Romero refers are, I suggest, not statistics but facts, which illustrate the wide discrepancy in charges indicated in the paper.

I think that Mr. Mellonie is not justified in referring only to the total increase in consumption when measuring progress. Surely the cost of providing those additional units must be brought into consideration, and the cost per unit measured at various stages during the progress in consumption. I agree that the criterion of " units sold per £ of distribution capital " is not a direct measure of service rendered, but, other things being equal, better service will be reflected in the rate of increase of the units sold per £. This is probably supported by Mr. Kirby's illustration of the relations between average price consumption and units sold per £ of distribution capital.

In reply to Mr. Crompton, I do not see why an overriding authority with statutory powers to decide tariffs should have the effect of retarding development. It is assumed that this authority would have a full knowledge of the costs and other factors pertaining to each district, and that it would be sensitive to the effect of a variation in charge upon consumption. Similarly, and in reply to Mr. Fennell, I do not suggest in the paper that it would be possible or wise for a uniform domestic tariff to be imposed at once and with the present distribution areas. I have referred on page 452 (vol. 81) to the impracticability, under present conditions, of obtaining uniformity in tariffs and charges on an equitable and satisfactory basis. But when two supply undertakings are merged into one a natural tendency arises to equalize charges and to bring the tariffs, i.e. the bases of charge for the previously separated undertakings, to a common basis, as I am sure Mr. Fennell will appreciate. I suggest that electricity is now so popular that competition from other forms of lighting and heating is not seriously to be feared provided the electricity charge conforms to modern standards.

Bristol Discussion

Mr. Fradsall-Smith's remarks have been largely answered in my general reply, which deals with the point raised by a majority of the contributors—that a constant or declining average in domestic consumption is generally to be expected. It is, of course, true that the larger undertakings with the highest proportion of power obtain a lower average revenue for domestic supplies, but it will be noticed that the ratio of domestic to power charges has increased to approximately 3 : 1 for those larger undertakings.

I should like to thank Mr. Bowden for his general support of the paper, and I quite agree that improvement in load factor is a matter which should receive close attention. Reconstruction of tariffs and charges towards uniformity must clearly keep this important matter in view. I should particularly like to commend for wide attention the important suggestion made by Mr. Bowden in the final paragraph of his contribution, where he refers to the need for a form of clearing house in regard to supply quotations.

In reply to Mr. Roberts, it is difficult to ascertain the average annual domestic consumption above which a two-part tariff should show advantage over flat-rate charges. Much more information must first be available

at some central source, of the tariffs, costs, and increase in demand, for each separate undertaking. As I have tried to show in the paper, where a distribution system is not hopelessly inadequate it is preferable to utilize those mains to the full extent as the means of lowering the cost of distribution per consumer.

I agree with Mr. Midgley that freedom of choice in carrying out financial arrangements and methods of statistics has been beneficial in the past and I hope that it will be retained by engineers in the future; but, as I am sure he will agree, electricity distribution has now developed to such an extent that its management has become a science in which statistics need to be co-ordinated between undertakings. I still consider that the relationship between average price and the resultant sales of electricity is definite, and that there is some law which relates these two factors. Service, publicity, etc., are valuable and necessary facilities to sales, but they are effective usually only in reducing the time-lag which often occurs between a reduction in price and the subsequent increase in sales.

Nottingham Discussion

Mr. Tucker's figures for the Loughborough undertaking (Table L) are very good, but it should be borne in mind that Table 2 in the paper shows only the average, grouped data, and that many individual undertakings will therefore show data which are considerably better than the averages. It is not possible, of course, to produce unchallengeable proof that the industrial load is subsidized by the domestic load. The principle of selling domestic supplies at the best price that we can get is quite sound, but I wished to stress in the paper that these prices must first be ascertained and then granted without delay. I am afraid that I must join issue with Mr. Tucker in his implication that the established forms of tariff are quite fair to consumers, whilst the proposed "fixed-consumer-charge" method is void of equity. The fixed charges in Table 15 are based on the present average costs, but Fig. 9 suggests that the average fixed charge for the country is falling each year. I would ask Mr. Tucker whether he would agree to reduce the fixed charge to the artisan's house if it fell so low as to produce an average cost per unit lower than his flat rate, at the same consumption. I appreciate and agree with the other matters which he discusses, and there are several suggestions that an upward trend may be commencing in the average domestic consumption.

Mr. Wadeson touches the most important factor in domestic consumption when he refers to the fact that the middle classes are not replacing their heating and cooking appliances. This is one of the most important facets of the question which I desired to present. As stated on page 430 of the paper, if the established consumers in, say, the year 1931 were increasing their consumption as one would expect, the total domestic consumption for 1934–35 should have been reached without the aid of any of the consumers connected from 1931 to 1935. Many of the contributors appear to have overlooked this masking of normal consumption due to the later connection of small new consumers. The present two-part tariffs for private houses are, I agree, largely rule-of-thumb, but my contention is that a scientific basis is often claimed for this rule-of-thumb method.

I have dealt with Mr. Ginno's main point in my earlier reply, but he will see that his contention, that the falling domestic average in Leicester is not unprogressive, is based on the assumption that the large number of assisted-wiring consumers will ultimately increase their consumption by a fairly large amount. Although it is probably not true for Leicester, yet in many cases this increase does not occur, often owing to domestic charges remaining too high and to the decision to reduce price *after* the increased consumption takes place. As I have already stated, uniformity in tariffs and charges should be accompanied by increased efficiency in service and management, etc., but we must primarily create the "will to buy" on the part of the consumer.

In reply to Mr. Rowland I do not think that the average proportion of power to domestic consumers is as low as it is for large towns such as, say, Salford. I must also refer to the fact that it is clearly indicated on page 430 of the paper that the ratio of power to domestic consumers adopted there is arbitrary and is assumed without full knowledge in order to arrive at an average consumption for combined lighting, heating, and cooking. Table 7 does not, of course, depend in any way upon this arbitrary division of consumers, and is based solely on the amount of total supplies for power and domestic purposes. Similarly, Table 13 is ". . . to indicate the approximate nature of the reduction in average consumer cost . . ." and can hardly be described as a suggested new tariff. Is it possible that the low average consumption of 630 units to which Mr. Rowlands refers is due to the fixed annual charge under the two-part tariff being too high, or is it possible that consumers are not satisfied with the method of assessing the fixed charge? Assuming a secondary charge of 0·5d. per unit, for example, the consumer with 630 units per year pays £2 17s. 3d. fixed annual charge and the consumer with 2 800 units pays £2 2s. 8d. I think, however, that Mr. Rowlands clearly indicates one of the obstacles to progress in the last paragraph of his contribution, where he refers to the cost of apparatus.

Mr. Brookes is, I think, quite right in his analysis of development of distribution, and the only question which arises is whether the increase of load nearer to the generating centre will be sufficient to neutralize the persisting high cost for the outer distribution areas.

I do not admit to Mr. Bayley that Diesel oil-engine plant is cheaper than the unsubsidized public supply cost of power for industrial purposes. The purpose of discussing domestic and power charges in the paper was to suggest that the differentiation which causes an average charge of, say, 3d.–6d. per unit to a small domestic consumer and perhaps 0·5d.–0·75d. per unit to a power consumer is quite unjustified in these modern days of supply. It is quite possible economically to offer a price of 1d. per unit or less to both classes of consumers, with the result that there would be a large increase in domestic consumption. My experience has been that a charge around £4·25 per kVA plus 0·45d. per unit will obtain all *normal* industrial power supplies and prove economical to both consumer and supply undertaking.

THE MECHANISM OF THE LONG SPARK*

By T. E. ALLIBONE, D.Sc., Ph.D., Associate Member.

(*Paper first received* 30*th September*, 1937, *and in final form* 21*st March*, 1938.)

SUMMARY

Study of the mechanism of the electric spark has been mainly confined to the short spark in homogeneous fields, or to the long spark provided by Nature in the form of the lightning flash. Following some early work of the author's on the characteristics of the impulse-voltage spark from a negatively or positively charged point electrode to earth, the author has further studied these discharges with the rotating camera to find the chronological sequence of discharge processes. Discharges preceding the main spark were observed irrespective of the polarity of the high-voltage electrode, the separation in time of the pre-discharge manifestation from the main spark being almost equal to the time-to-sparkover as recorded by the cathode-ray oscillograph. These discharges have been studied in air at atmospheric and lower pressures, and it has been shown that the pre-discharge is a "leader stroke" in the strict sense of the word as applied to the lightning discharge: a "leader" blazes an ionized path from the high-voltage electrode (of either polarity) to earth and is then followed by the return or main stroke of the spark from earth to the high-voltage electrode. Under certain conditions leader strokes have been shown to develop from both electrodes simultaneously. The leader stroke always exhibits branching in the direction of propagation; the main stroke follows some of the more important branches but does not develop fresh branches. The direction of branching of the spark discharge has been shown to furnish the criterion for the direction of propagation of the leader stroke.

CONTENTS

(1) INTRODUCTION

The study of the conduction of electricity through gases has provided a scientific literature probably more prolific than exists on any other subject, yet in spite of its antiquity new investigations are constantly throwing a fresh light on some of the many unexplained phenomena. It would be out of place here to review the earlier researches; it is sufficient to refer to the standard textbooks, such as Sir J. J. Thomson's "Electrical Conductivity of Gases," and only to note briefly the latest researches bearing on the subject and particularly on the experiments to be described. Much of the earlier work was done with steady potentials applied to parallel-plate electrodes in gases at low pressures: the more recent work has been done mostly with impulse voltages and with the cathode-ray oscillograph or high-speed camera, and another great contribution to knowledge has come from the photographic study of the lightning discharge. The author's experiments concern photographic and oscillographic studies of the long spark, a phenomenon falling between the lightning flash and the short discharge investigated so extensively for over 50 years.

(2) REVIEW OF EXISTING KNOWLEDGE OF THE SPARK DISCHARGE

The subject is so enormous that it is almost beyond the powers of any but the extreme specialist to present a comprehensive view of it. We are indebted to Prof. Loeb† for a critical survey of the present position of the science, and the following is but a small part of a very complicated whole.

A spark occurs between two electrodes when the conduction current in the gas between them rises very rapidly from extremely low values to values of the order of amperes, values sufficient to produce intense luminosity in the visible and ultra-violet spectrum. The spark is initiated by at least one electron being accelerated in the electric field between the electrodes and causing ionization of the gas molecules by collision: thereafter, multiple ionization by collision and other processes producing ions may operate to increase the current to the value mentioned above, when a spark occurs. The presence of at least one electron between two electrodes at any moment is assured in all but the most exceptional cases‡ by photo-electric action in the gas or at the electrodes, by radioactivity, or by cosmic radiation. In an electric field approaching the critical breakdown field, chance-occurring electrons will be accelerated and by collision will produce ions and more electrons. This may be called the primary ionization process, and it is accompanied by some or all of the following secondary ionization processes: (i) Emission of light by the ionized (or

* This paper, which has been awarded the Coopers Hill War Memoral Prize and Medal for 1937, will be read and discussed at an Ordinary Meeting of The Institution next Session.

† L. B. LOEB: "Review of Modern Physics" (July, 1936).
‡ By special preparation of gas, J. W. Flowers (*Physical Review*, 1935, vol. 48, p. 954) was able to obtain extremely high over-voltages on gaps, through the absence of electrons which could initiate a spark.

excited) molecules, and absorption of that light by other molecules (generally of a different element from that of the ionized molecule), accompanied by photo-electric emission. (ii) Emission of light by the ionized (or excited) molecules and absorption of that light by the cathode, accompanied by photo-electric emission at the cathode. (iii) Electron emission from the cathode due to positive-ion bombardment of the cathode.

In addition, one or two other secondary ionization processes may ensue, but these are either not very well understood or they arise in special cases only: they will therefore not be discussed.

The primary ionization process, studied by Townsend and his co-workers, has been recently fully re-investigated* over an extended range of variables, and it is found experimentally that the Townsend negative ionization-coefficient α (the number of electrons produced by 1 electron moving 1 cm. in the direction of the field)

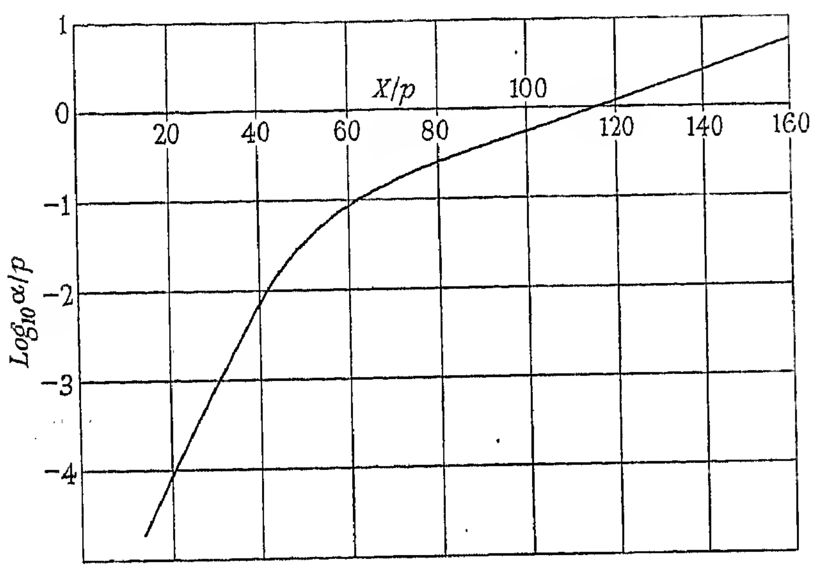


Fig. 1.—Variation of α/p with X/p: curve for pure N_2 (Posin).
α = Townsend coefficient, p = pressure in millimetres of mercury, X = field strength in volts per cm.

varies with the field strength in a complex threefold manner. Fig. 1 shows a curve in which $\log_{10}(\alpha/p)$ is plotted against X/p, where p is the pressure in mm. of mercury and X is the field strength in volts per cm. For low values of X/p, α/p varies as $e^{X/p}$; for higher values of X/p, α/p varies as $\left(\frac{X}{p} - \text{Constant}\right)^2$; and for still higher values of X/p, α/p varies as $(X/p)^{\frac{1}{2}}$. The field-strengths causing breakdown between parallel-plate electrodes at atmospheric pressures and between point electrodes lie in the first two regions of the curve, but before breakdown takes place the current passing between the electrodes exceeds the value given by the simple Townsend equation. This increase of current was formerly ascribed to ionization in the gas by positive ions, but it is now known definitely that this cannot occur with the field strengths normally encountered at breakdown, and the aforementioned three secondary ionization processes have been substituted for Townsend's positive-ion ionization.

Secondary process (i) is important in heterogeneous gases (and only in very carefully-prepared experiments are the gases *not* heterogeneous), since most of the characteristic radiation potentials of an atom are lower than its ionization potential, and therefore radiation caused by ionization is almost incapable of causing ionization in like atoms but may very efficiently cause ionization in unlike atoms. The process is also probably important in long discharges in supplying a copious source of electrons ahead of the advancing discharge.

Secondary process (ii) is considered to be very important as the radiations of the corona discharge and of the non-luminous discharge (the *entladung-strahlung*) which is known to exist before the luminous discharge develops are of very short wavelength and are therefore highly efficient in producing photo-electric emission from metals. This process is important for short discharges but clearly cannot apply to long sparks.

Secondary process (iii) is at present somewhat uncertain as experiments depend to such a great extent on the preparation of the electrodes: there are many experiments pointing to the process being important, at least for small sparks, but not for long sparks and for lightning discharges.

It is interesting to note that mathematical analysis of the results of secondary processes (ii) and (iii) lead to equations for the spark very similar in form to that developed and verified experimentally by Townsend and others, based on the discredited positive-ion ionization theory.

For long gaps the primary and secondary ionization processes are almost certainly assisted by the formation of space charge and by the consequent distortion of the electric field. Assuming that the positive ion formed in the primary process does not migrate in the short time taken for the development of a spark, very considerable space-charge will be created even by the action of only one primary electron. Thus in a field of 30 kV per cm. at atmospheric pressure ($X/p = 40$), one primary electron yields α electrons—and therefore positive ions—within the first centimetre of its path in the direction of the field; this amounts to 10^4 ions: in 2 cm. the electron yields 10^8 ions, etc. These figures would be further increased by the secondary processes enumerated. The presence of the space-charge results in greatly increased gradients at the boundary of the ionized channel, and consequent increased ionization coefficients. Cravath and Loeb* have shown how the distortion of the thundercloud field by space charge can explain the speed of formation of the "leader" stroke to the lightning discharge as photographed by Schonland, Malan, and Collens,† although the average electric field between cloud and earth is only of the order of a few kilovolts per centimetre. Even at small electrode-spacings and with homogeneous electric fields, space charge appears to play an important role, as shown by Dunnington,‡ White,§ and von Hippel and Franck,‖ who observed that the spark in addition to starting at the cathode sometimes started simultaneously at the middle region of the gap for gaps of the order of 1 cm. White suggests that breakdown is determined by the location of the space charge. Calculations by Varney

* See D. Q. Posin: *Physical Review*, 1936, vol. 50, p. 650, and earlier papers there quoted.

* A. M. Cravath and L. B. Loeb: *Physics*, 1935, vol. 6, p. 125.
† B. F. J. Schonland and H. Collens: *Proceedings of the Royal Society*, A, 1934, vol. 143, p. 654; B. F. J. Schonland, D. J. Malan, and H. Collins: *ibid.*, 1935, vol. 152, p. 595.
‡ F. G. Dunnington: *Physical Review*, 1931, vol. 38, p. 1535.
§ H. J. White: *ibid.*, 1934, vol. 46, p. 99; and 1936, vol. 49, p. 507.
‖ A. von Hippel and J. Franck: *Zeitschrift für Physik*, 1929, vol. 57, p. 696.

and others* on the role of space charge in altering the Townsend ionization-coefficients showed that the coefficient α can be increased on account of field distortion in the regions of moderately low field-strengths where α/p varies as $e^{X/p}$ or $(X/p)^2$, the regions corresponding to atmospheric pressures and large gap spacings; and it is suggested that field distortion can fully account for spark formation without the agency of the three secondary processes enumerated above. From Fig. 1 it will be readily appreciated how a small increase in X/p causes a large increase in the value of α; as X/p changes from 40 to 60, α changes from 8 to 80.

A spark requires a definite time for its formation. One of the outstanding difficulties of the Townsend theory of spark formation was the time required for spark formation. If appreciable movement of positive ions is to take place (ions moving with velocities of, say, 10^5 cm. per sec.) in order to furnish secondary ionization to create a spark, times of formation of at least 10^{-5} sec. will be required for short gaps, whereas Burawoy,† Rogowski,‡ and others§ showed that sparks could occur in 10^{-7} sec. to 10^{-8} sec. More recent study has shown that the total time-lag of spark formation may be divided into two portions: a statistical time-lag depending on the chance of an initiatory electron appearing near the cathode, and a formative time-lag, the time for the spark to develop across the gap once the initial ionization processes have commenced. The statistical time-lag is decreased by irradiating the cathode with ultra-violet light; the formative time-lag may be decreased by applying voltages in excess of the minimum sparkover voltage. Dunnington|| studied the variation of time-lag in homogeneous fields with electrode-spacing and with pressure, and showed that the time-lag increased with diminishing pressures; the increase being rapid below a pressure of 45 cm. of mercury. The time-lag also increased with increasing electrode-separations, at least up to that separation at which the mid-gap streamer already mentioned occurred: thereafter the time-lag remained almost constant, thus pointing to an increased speed of spark formation due to space charge. White¶ measured the speed of spark formation and found it to be about $1 \cdot 5 \times 10^7$ cm. per sec., almost the speed of electrons at that field intensity. With over-voltages, Wilson** obtained even shorter time-lags, times too short for an electron to cross the gap, and suggested that the lag was only the time necessary for the secondary processes to build up to such a value that visibility of the radiating atoms ensues.

The above work was all done with homogeneous electric fields, i.e. fields which were homogeneous before ionization produced distortion. With heterogeneous fields the situation is different. In the first place, with widely differing electrode-shapes (limits of point and plane) discharge usually occurs first at the smaller electrode, whether it be cathode or anode, earthed, or connected to a high-potential source; the sparking potential is usually lower when the smaller electrode is positive.* The familiar Lichtenberg figures of positive and negative discharges from a point on a photographic glass plate to an earthed electrode on the reverse side of the plate indicate an interesting difference between discharges of opposite polarity: the positive discharges are very fernlike, with multiple branches, the negative discharges radiate in fan-like bunches with less branching, and the radius of the negative figure is smaller than that of the positive figure for the same voltage. In each case, the discharge proceeds in the direction away from the point electrode, though obviously the negative carriers (electrons) move in a direction opposed to the electric field. Sparkover occurs when the gradient at the extremity of the discharge at any instant is still large enough to produce sufficient ionization by collision for the maintenance of the discharge: ionization by photoelectric emission at the cathode does not affect the discharge in long gaps. The value of X/p at the surface of the smaller electrode at which discharge is first seen is approximately equal to the value which would result in the passage of a spark in a homogeneous field, but higher gradients are required before a spark passes in the heterogeneous field. The breakdown voltage of long gaps is not influenced by ultra-violet radiation of the electrodes, and the time-lag of discharge is larger than for homogeneous fields. Typical results for time-lags for the extreme types of electrodes (point/plane) show† that the lags for positive point electrodes increase linearly with spacing: for negative point electrodes the lags are much smaller and do not increase much with spacing. The lag is probably the true formative lag, and not partly a statistical lag, as the value of X/p at the point is so very high. There is evidence too‡ from photographic observations that the lag is the true formative lag. The theory to explain the growth of the negative and positive discharges from point electrodes was given by Simpson§ and will be referred to later in the paper. More recently, Goodlet|| has advanced a theory for the long spark which goes beyond Cravath and Loeb's¶ theory in that it attempts to set a lower limit to the speed of propagation of the negative discharge.

With regard to the very long discharge of the lightning flash, Walter** showed that frequently very many partial discharges from cloud towards earth precede the first complete flash, and then a number of other complete flashes to earth follow, at intervals, over the same track. A recent study by Schonland and Collens†† in South Africa with the Boys rotating camera has shown that, in addition to the number of pre-discharges which partially bridge the gap to earth, one discharge finally reaches the ground and immediately an upward-growing intense discharge develops from ground to cloud. This " return stroke " or " main stroke " carries the large currents of thousands of amperes usually associated with the lightning flash, and it follows exactly the path blazed

* R. N. Varney, H. J. White, L. B. Loeb, and D. W. Posin: *Physical Review*, 1935, vol. 48, p. 818.
† O. Burawoy: *Archiv für Elektrotechnik*, 1926, vol. 16, p. 186.
‡ W. Rogowski: *ibid.*, 1926, vol. 16, p. 496; and 1928, vol. 20, p. 99.
§ R. Tamm: *ibid.*, 1928, vol. 20, p. 235; J. J. Torok: *Transactions of the American I.E.E.*, 1928, vol. 47, p. 349; J. W. Beams: *Journal of the Franklin Institute*, 1928, vol. 206, p. 809.
|| *Loc. cit.*
¶ *Loc. cit.*, and *Physical Review*, 1936, vol. 49, p. 507.
** R. R. Wilson: *Physical Review*, 1936, vol. 50, p. 1082.

* Noted by Faraday.
† T. E. Allibone, W. G. Hawley, and F. R. Perry: *Journal I.E.E.*, 1934, vol. 75, p. 670.
‡ T. E. Allibone and B. F. J. Schonland: *Nature*, 1934, vol. 134, p. 736.
§ G. C. Simpson: *Proceedings of the Royal Society*, A, 1926, vol. III, p. 56.
|| B. L. Goodlet: *Journal I.E.E.*, 1937, vol. 81, p. 1.
¶ *Loc. cit.*
** B. Walker: *Annalen der Physik*, 1903, vol. 10, p. 393.
†† *Loc. cit.*

out by the pre-discharge or leader stroke which carries only a small current of the order of amperes. It has been established that in general there is a leader stroke to each of the subsequent main strokes of a multiple lightning flash, although a distinction has been drawn between the leader stroke to the first main stroke and the leaders to the subsequent strokes. The leader to the first main stroke is stepped and travels with a mean speed of the order of $1 \cdot 5 \times 10^7$ cm. per sec., although individual steps move forward in jerks with a speed of about 100 times the above figure; the leaders to the subsequent strokes are not in general stepped, and as they move over an ionized path their speed is of the order of 2×10^8 cm. per sec. The lightning flashes so described are believed to emanate from negatively-charged clouds, and no discharges of the leader-stroke/main-stroke type have yet been recorded which can definitely be ascribed to positively-charged clouds, so that the positive leader-stroke has not yet been shown to exist. In the laboratory, however, photographs of long sparks from positive point-electrodes obtained by Allibone and Schonland* have already shown that a pre-discharge or leader stroke takes place immediately before the main spark occurs, although hitherto the photographs have not shown the track of the leader stroke over the whole of the gap from point to plane. Strigel† was unable to obtain confirmation of the author's results, but they have been confirmed recently by Stekolnikov.‡ This point will be referred to later in the paper.

(3) THE SPARK DISCHARGE IN INHOMOGENEOUS FIELDS AT ATMOSPHERIC PRESSURE

Experiments on spark phenomena are most conveniently performed with impulse voltages, mainly because the voltage can be applied with such great rapidity and for such short times, and also because of the ease with which the cathode-ray oscillograph may be applied to the study of time-lags and breakdown. In all the following experiments impulse voltages were used having a smooth voltage/time characteristic rising to maximum value in times of the order of 1–50 microsec. and then declining to half value in times varying from 30 to 300 microsec.

The general background of the experiments is based on previous work of the author and his colleagues§ on the point-plane gap at large spacings (greater than 10 in.) and at atmospheric pressure. Briefly, for conditions representing the minimum impulse sparkover voltage, the negative sparkover of a given point-plane gap is nearly twice as high as the positive sparkover voltage, but the time-lag of sparkover is very much smaller: and for the point-point gap, the positive and negative sparkover voltages are almost identical and lie about midway between the corresponding voltages for a point-plane gap of the same spacing; the time-lags are the same for both polarities and are also midway between the lags for the point-plane gap. These extremes of gaps afford an interesting subject for further investigation.

The experiments were in part aided by the use of a rotating camera having a film speed of 1/24 mm. per microsecond and a lens (glass) aperture of $f/2 \cdot 9$: later a quartz ultra-violet flint-glass lens of $f/4$ aperture was used, giving finer records. A satisfactory film was found to be Messrs. Ilford's "Oscillographic Film Type F," but Selochrome or panchromatic film gave good records. Films were over-developed as judged by the usual time/temperature rule in order to bring out the fine tracery of the corona discharge accompanying the strong main spark.

(a) Observations with the Stationary Camera

The interesting characteristic of the discharge at a voltage just lower than the sparkover of a point-plane gap is that it is almost impossible to distinguish between the positive and the negative corona discharge. In absolute darkness the corona can be seen to extend from the point electrode to the plane, and if the plane has a trace of grease or oil on it this can be seen to fluoresce in tufts all over the plane, indicating that discharge is continuous from point to plane even though no spark develops. At the point the discharge is whiter, and of course more concentrated: with positive polarity the streamers at the point appear to be curved downwards towards the plane, whilst with negative polarity they extend in straighter lines from the point: in this way the two types of discharge resemble the Lichtenberg figures radiating from a point. The fine blue tracery is not easily reproduced photographically as it is a three-dimensional discharge; and the lens has only a small depth of focus. Fig. 2 (see Plate 1, facing page 516) is one of the best records so far obtained in the absence of complete flashover: the tufts on the earth plane are just distinguishable (positive polarity 10^6 volts). When the point is of negative polarity, streamers often develop from the earth plane towards the cathode at voltages just below flashover (as mentioned above, the average voltage gradient on negative is nearly twice that on positive polarity for the same gap): such discharges have rarely been seen to rise from the plane when the high-voltage point electrode is of positive polarity.

When sparkover takes place the whole of the corona discharge can still be seen (with a little experience) in spite of the intense brilliance of the main spark. The negative discharge generally does not divide into a few main branches, though a fine tracery of branches can be seen close to the main channel: the positive discharge often divides as it approaches the plane, and each fork is shrouded with fine tufts of discharge. It was the strong resemblance of this positive branched discharge to the typical lightning discharge that led Sir George Simpson* to regard the direction of branching of the lightning channel as a criterion of the polarity of the flash. If, however, from the earthed plane a point projection is raised, then, with a negative discharge, streamers of considerable strength develop from this earthed point and grow to meet those from the high-voltage point. When the earthed plane is studded with a great many point projections an extensive forest of streamers develops from earth and, at voltages sufficient to create a spark, the main discharge from the high-voltage point divides into many branches directed towards the discharge from

* *Loc. cit.*
† R. Strigel: *Wissenschaftliche Veröffentlichungen aus den Siemens-Werken,* 1936, vol. 15, p. 68.
‡ I. S. Stekolnikov: *Elektrichestvo,* 1937, vol. 8, p. 49.
§ *Journal I.E.E.,* 1934, vol. 75, p. 670.

* *Loc. cit.*

H.T. point

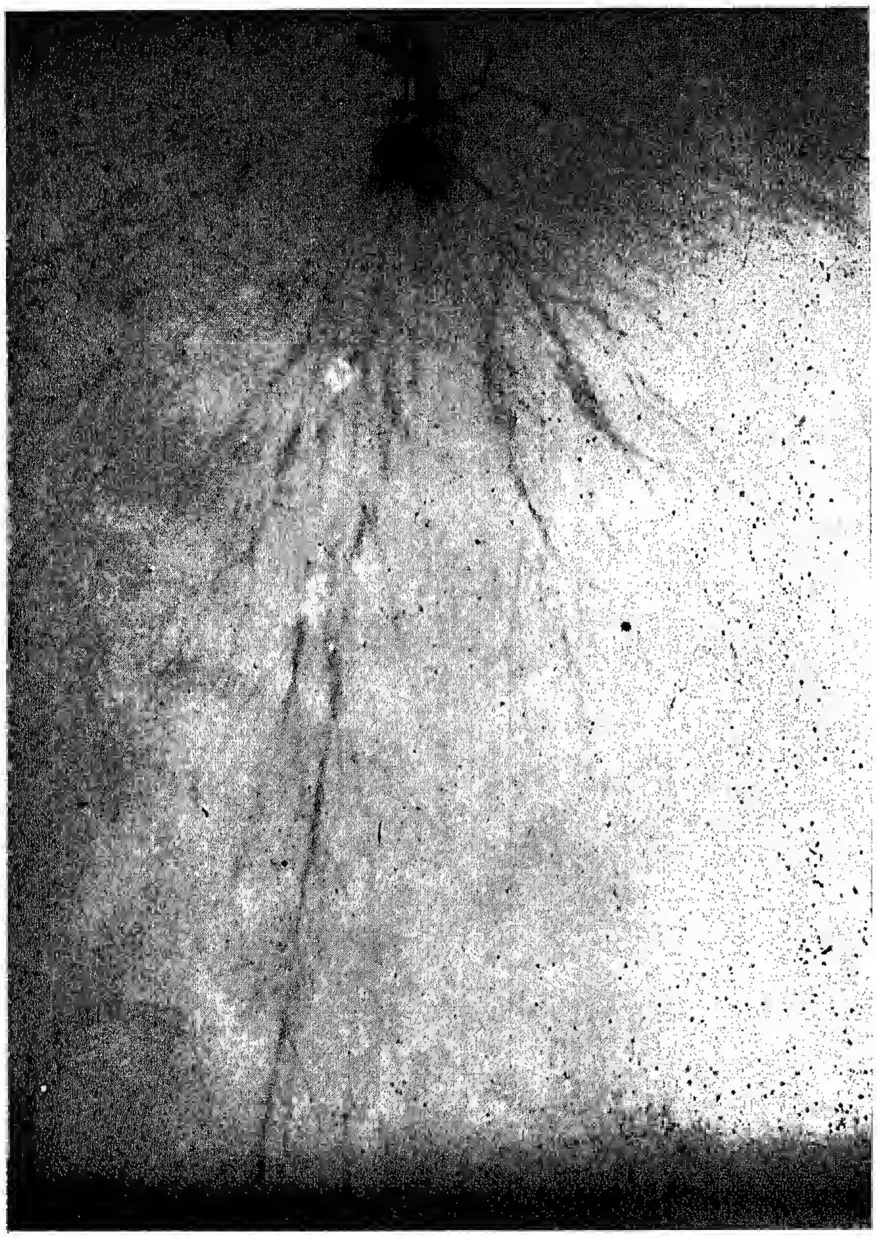


Fig. 2.—Corona discharge from positive point to negative earthed plane electrode at voltage just below sparkover (10^6 volts: 1/50 microsec. impulse wave).

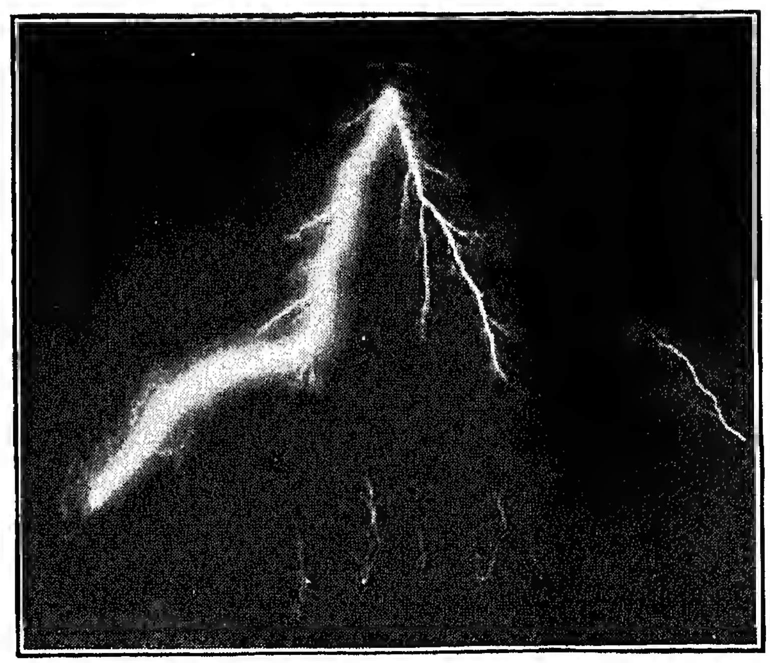


Fig. 3.—Sparkover from negative point to positive earthed plane electrode from which project many short points (10^6 volts). (Note the long discharge ascending from earth to meet the downward branched discharge.)

Plate 2

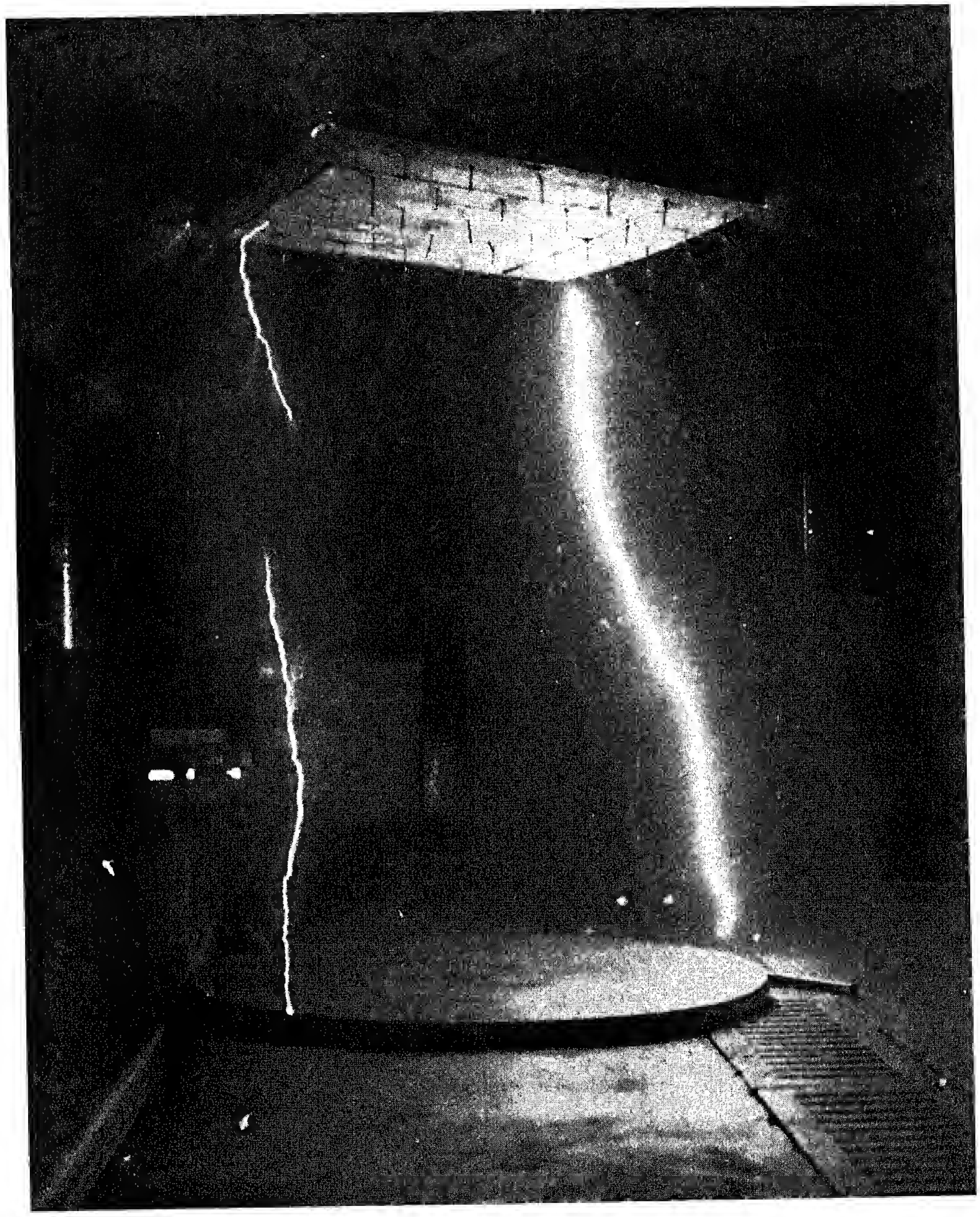


Fig. 4.—Sparkover from an extensive pointed high-voltage negative electrode to an earthed electrode. Note the upward and downward branched streamers to left of the main spark. The earthed electrode has many points of high local stress from which upward branched streamers develop.

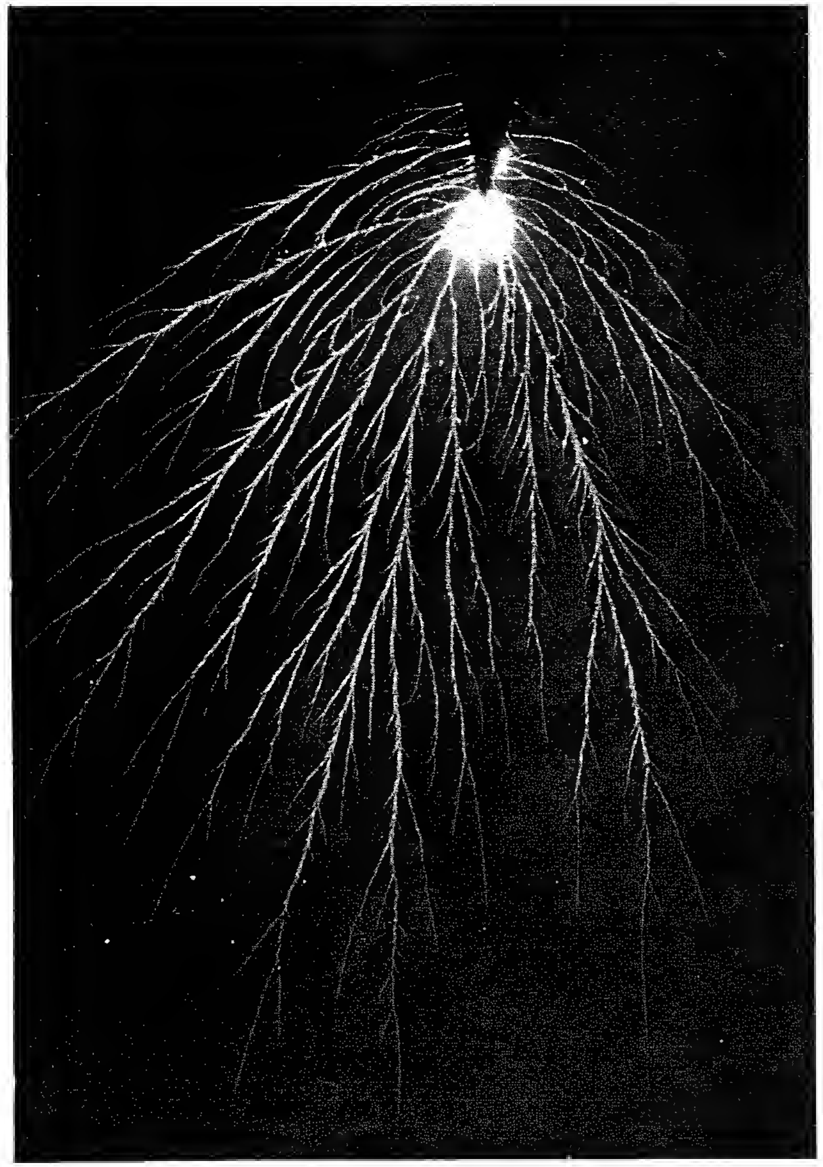


Fig. 5A.—Lichtenberg figure, positive point/plane earthed cathode.

Fig. 5B.—Lichtenberg figure, negative point/plane earthed anode.

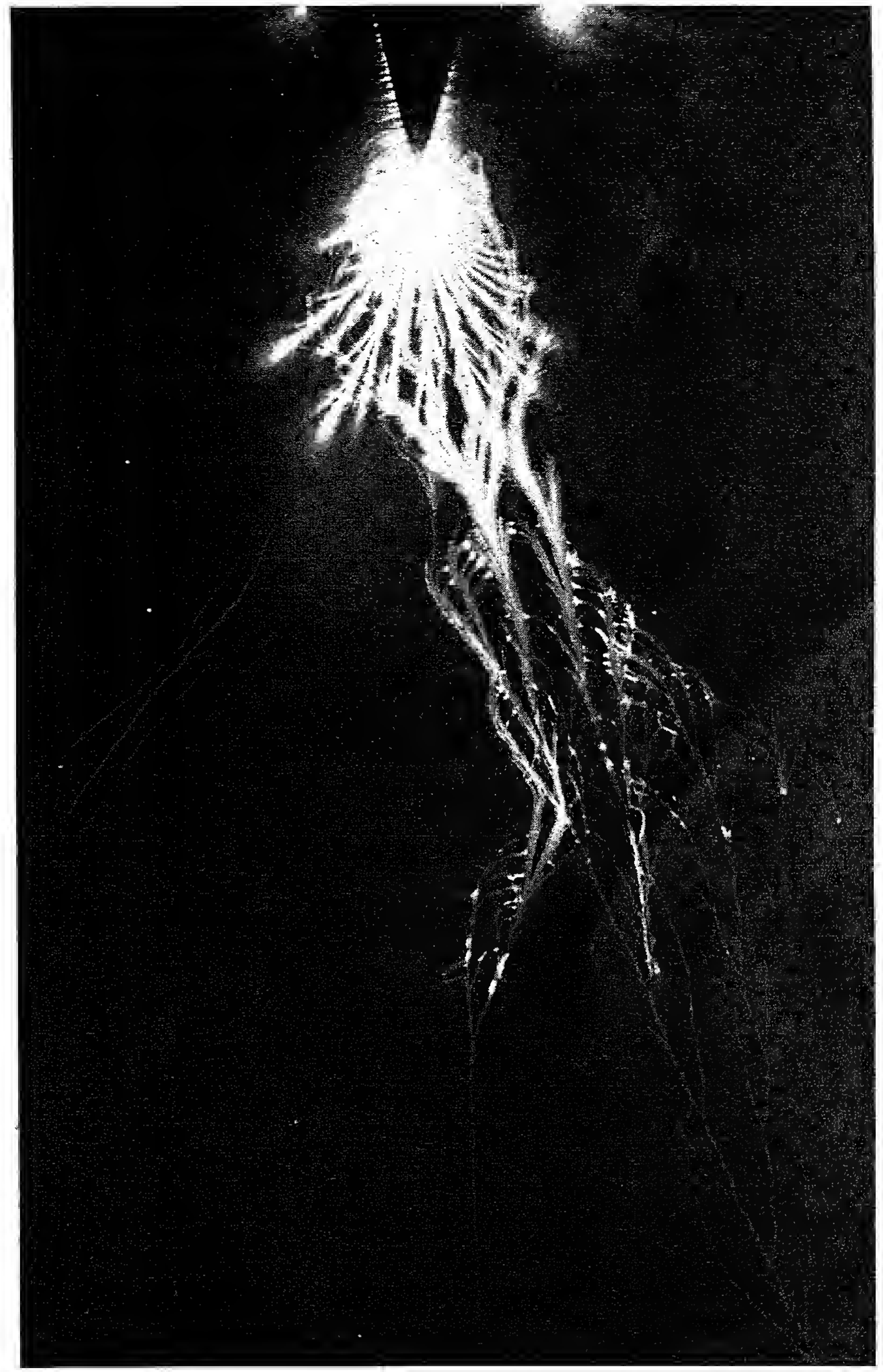
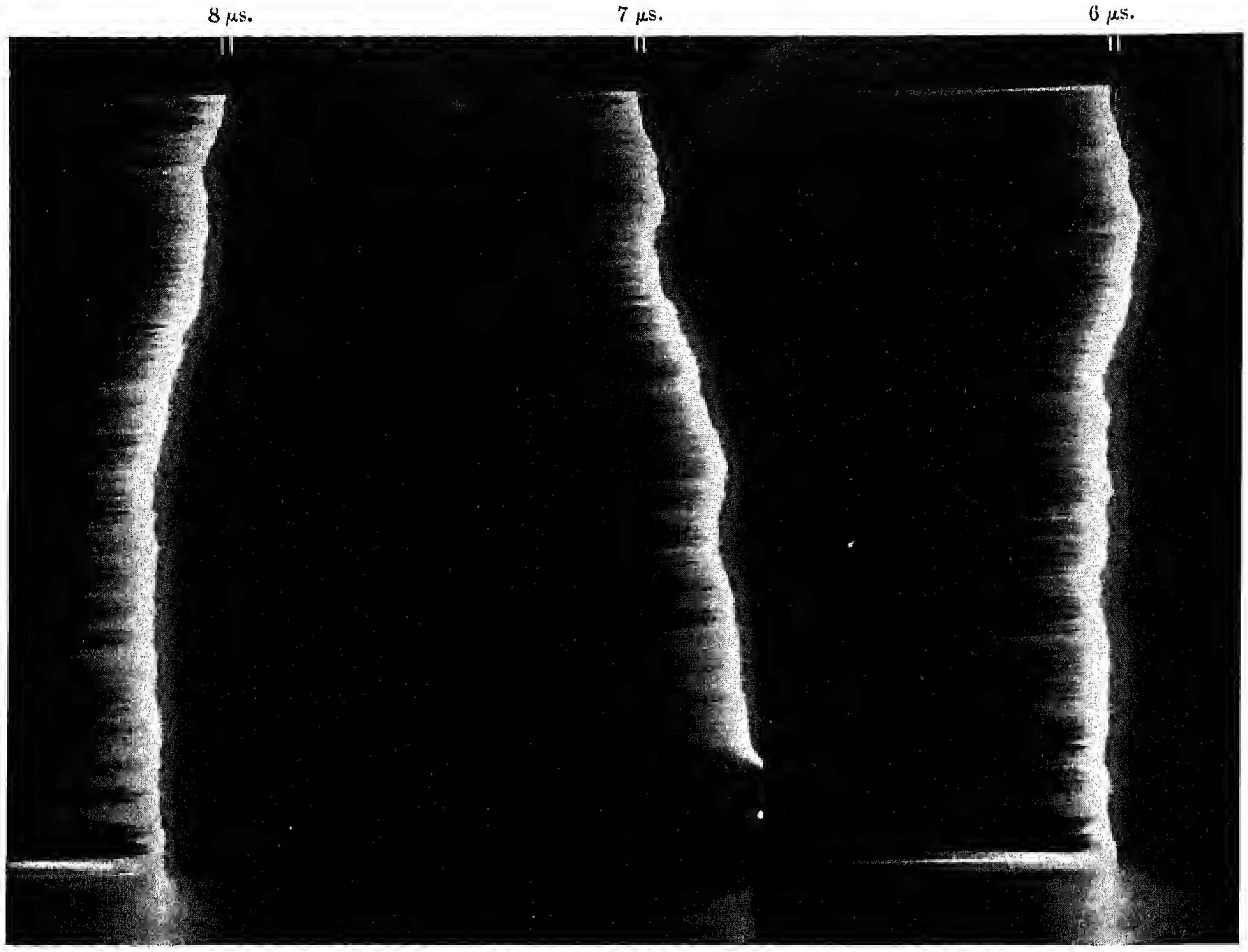


Fig. 5C.—Lichtenberg figure, negative point/plane earthed anode with few small projections. (Note the ascending positive discharge figure reaching the negative discharge: voltage just below sparkover.)

Plate 4

(a)



(b)

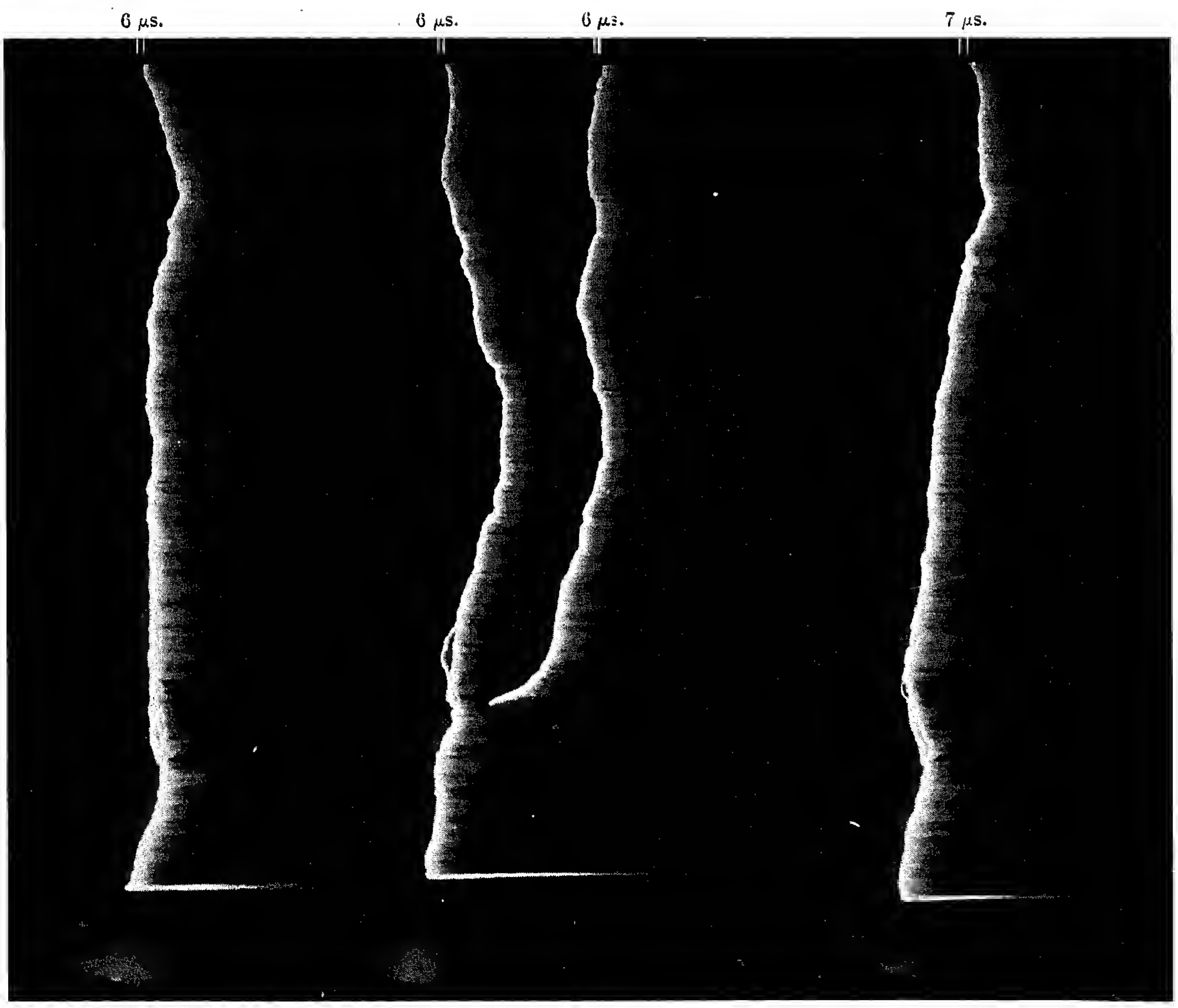


Fig. 6.—Rotating-camera photographs of sparks: atmospheric pressure.

(a) Negative point/plane: 3 separate sparks each preceded by a "leader" discharge 7 microsec. in front of main spark.
(b) Positive point/plane with projecting points: 4 separate sparks each preceded by a leader discharge 6 microsec. in front of the main spark.

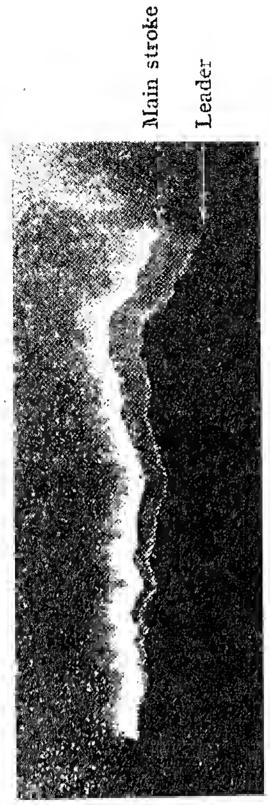


Fig. 7A.—Leader and main stroke of a lightning discharge. Time between leader and main stroke = 300 microsec. (From *Nature*, 1933, vol. 132, p. 407.)

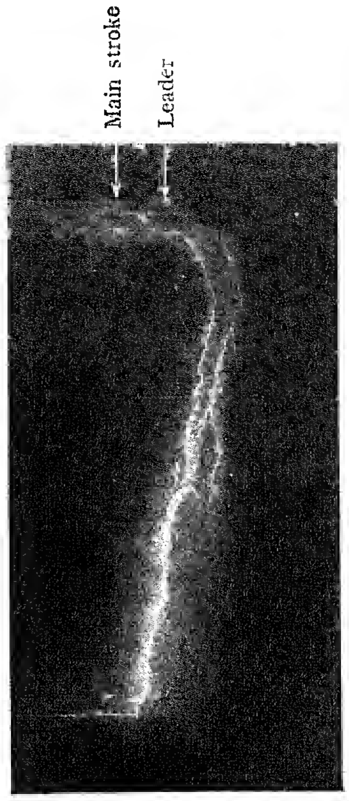


Fig. 7B.—Leader and main stroke of a laboratory spark discharge. Point positive/earthed plane. Time between leader and main stroke = 84 microsec.

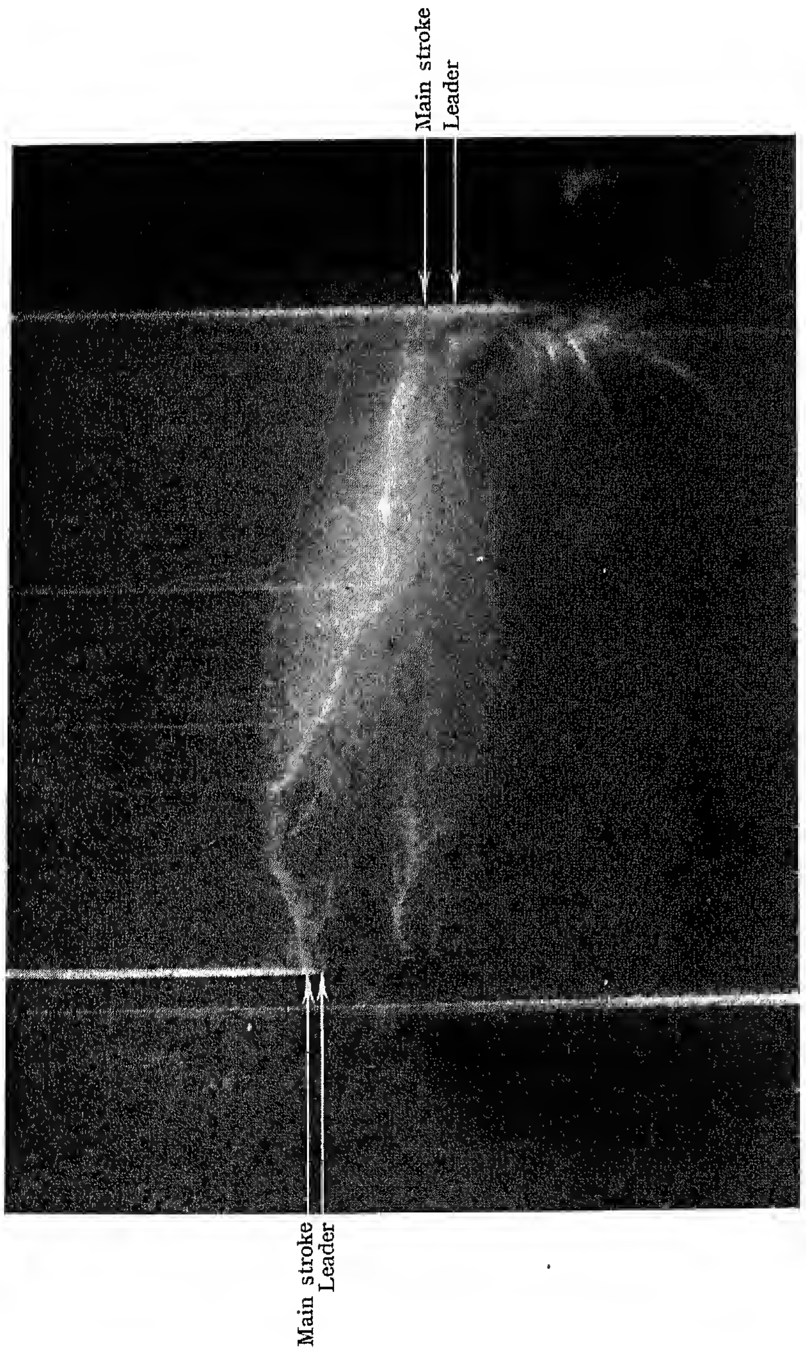


Fig. 8A.—Leader stroke from high-voltage point cathode to plane earthed electrode.

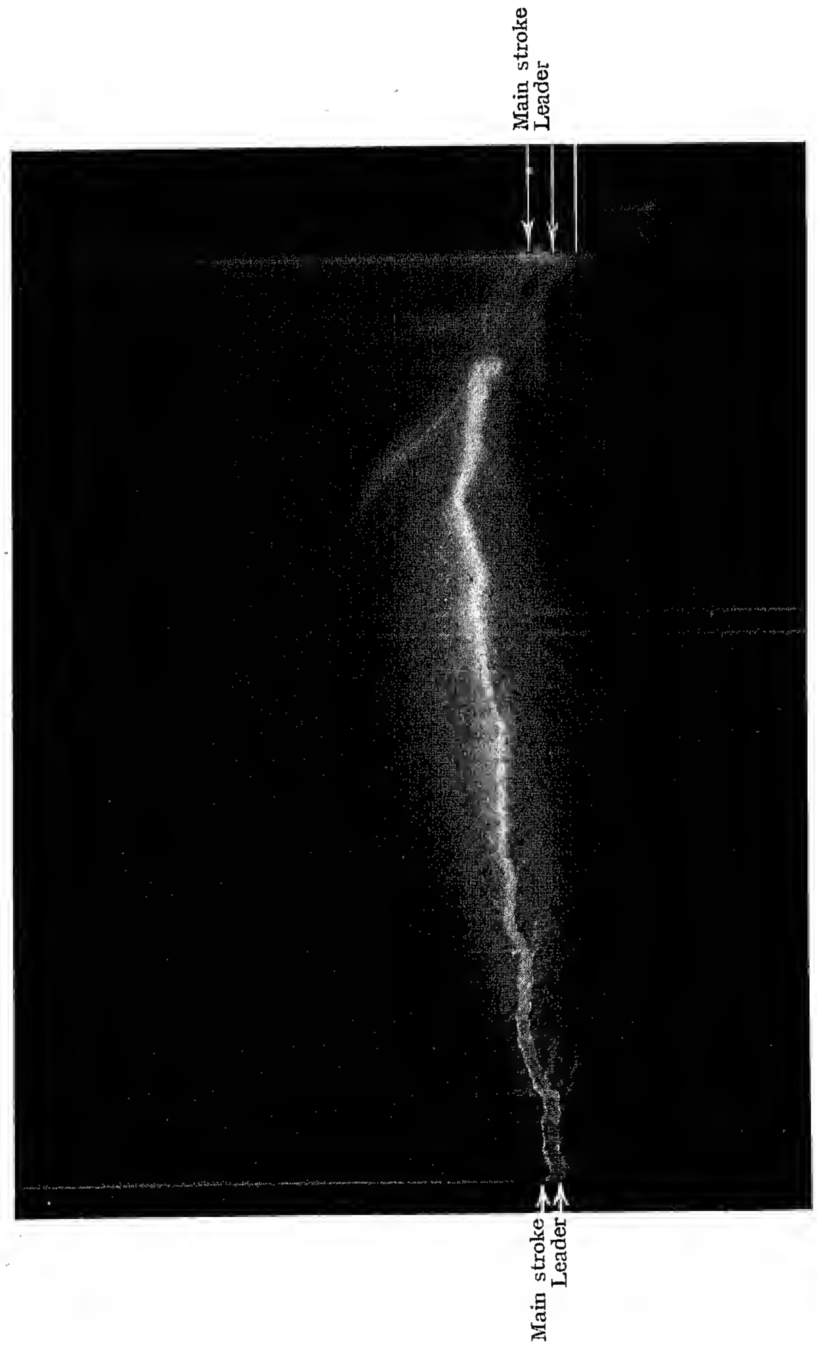
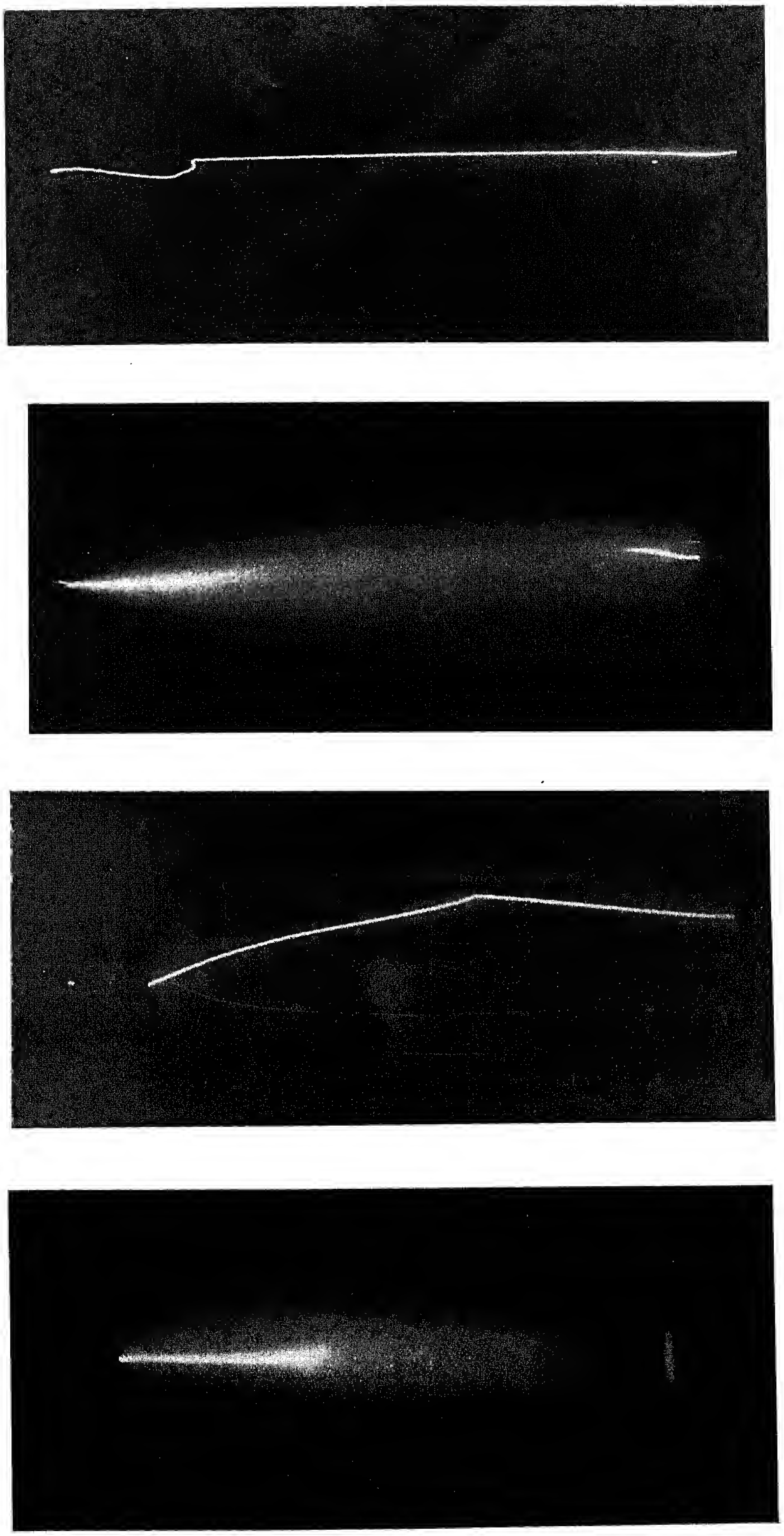


Fig. 8B.—Leader stroke from high-voltage point cathode to a short pointed projection from a plane earthed electrode.

Plate 6



(a) (b) (c) (d)

Fig. 9.—Stationary-camera photographs of discharges at low pressure.

(a), (b) Point anode/plane cathode. (a) Pressure = 1·2 cm. Hg. (b) Pressure = 6 cm. Hg.

(c), (d) Point cathode/plane anode. (c) Pressure = 1·2 cm. Hg. (d) Pressure = 6 cm. Hg.

[Note that the upward-directed streamer from the anode in (c) becomes the long straight upward-directed spark in (d).]

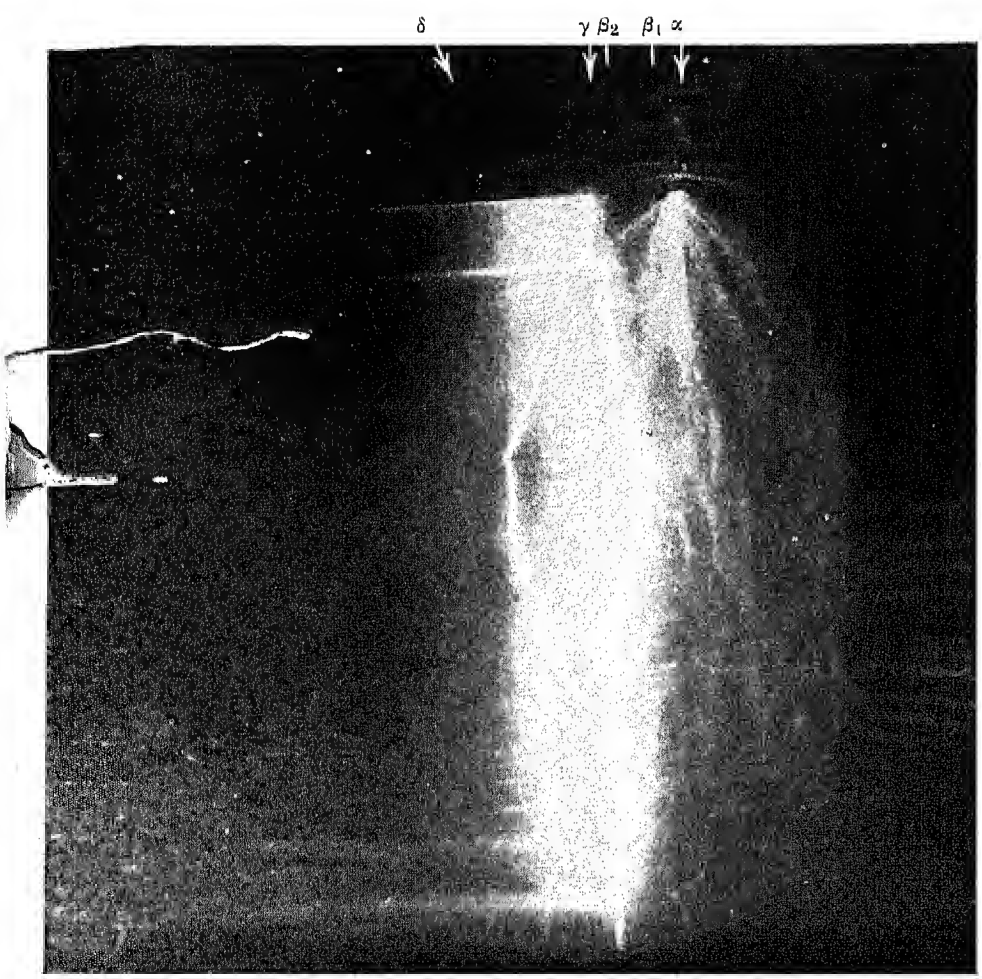


Fig. 10A.—Rotating-camera photographs of impulse-voltage discharge at low pressure: point anode/plane cathode.

Pressure = 6 cm. Hg.
α = corona developing rapidly after voltage is applied.
β_1 = first sharply defined leader (10 cm. long).
β_2 = second leader.
γ = main stroke.
δ = reflection of main stroke at the glass tube.
α, γ = 65 microsec.

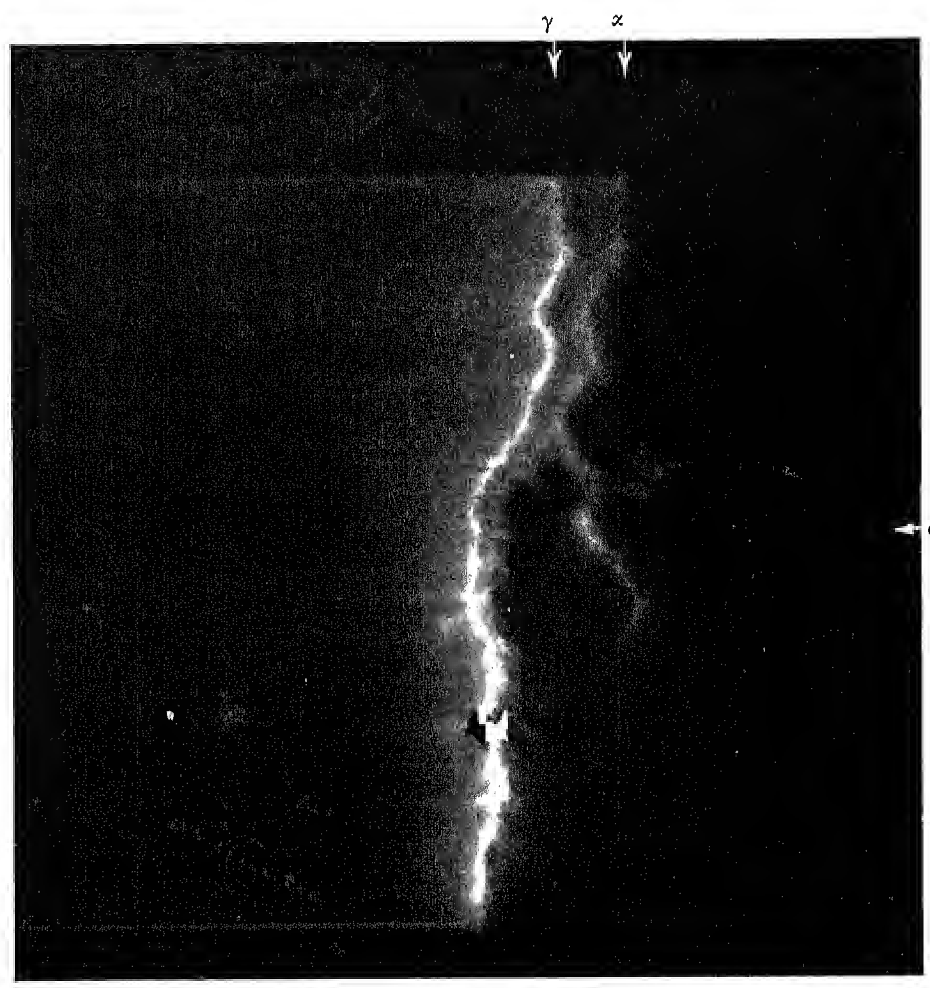


Fig. 10B.—Rotating-camera photographs of impulse-voltage discharge at low pressure: point anode/plane cathode.

Pressure = 24 cm. Hg.
α = leader developing as the voltage is applied.
γ = main stroke.
ϵ = positive-leader branch followed by main-stroke branch.
α, γ = 51 microsec.

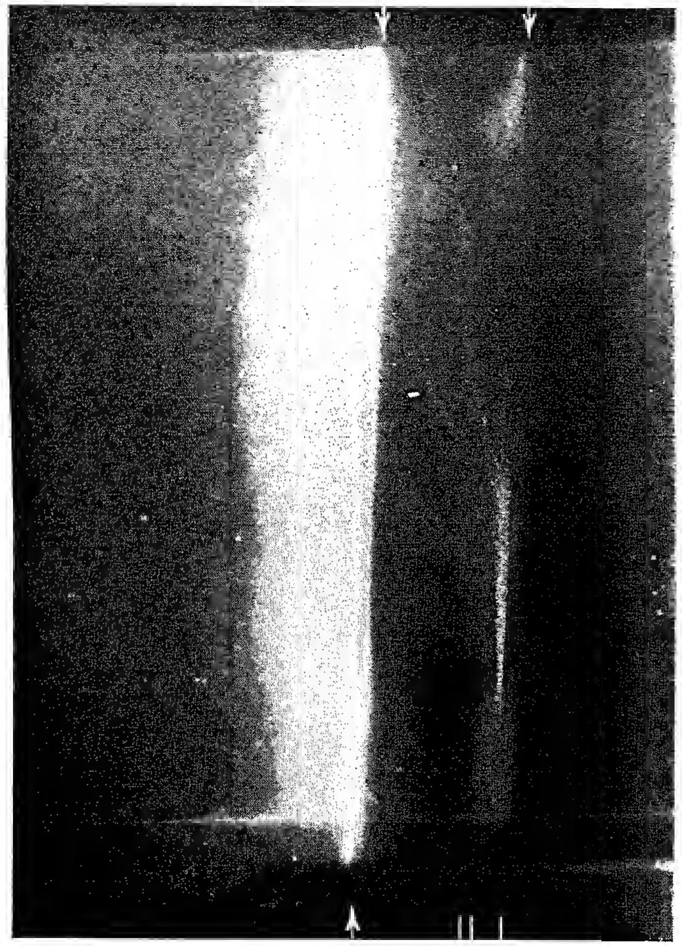


Fig. 10C.—Rotating-camera photographs of impulse-voltage discharge at low pressure: point cathode/plane anode.

Pressure = 6 cm. Hg.
α = negative corona.
β = positive corona from anode upwards.
β_1 = mid-gap streamer.
β_2 = mid-gap streamer at later instant.
γ = main stroke and reflection in glass.
α, γ = 108 microsec.

Fig. 10D.—Rotating-camera photographs of impulse-voltage discharge at low pressure: point cathode/plane anode.

Pressure = 24 cm. Hg.
α = negative leader branching downwards.
β = positive leader branching upwards.
γ = main stroke.
ϵ = strong upward-directed positive branching.
α, γ = 19 microsec.
β, γ = 16·8 microsec.

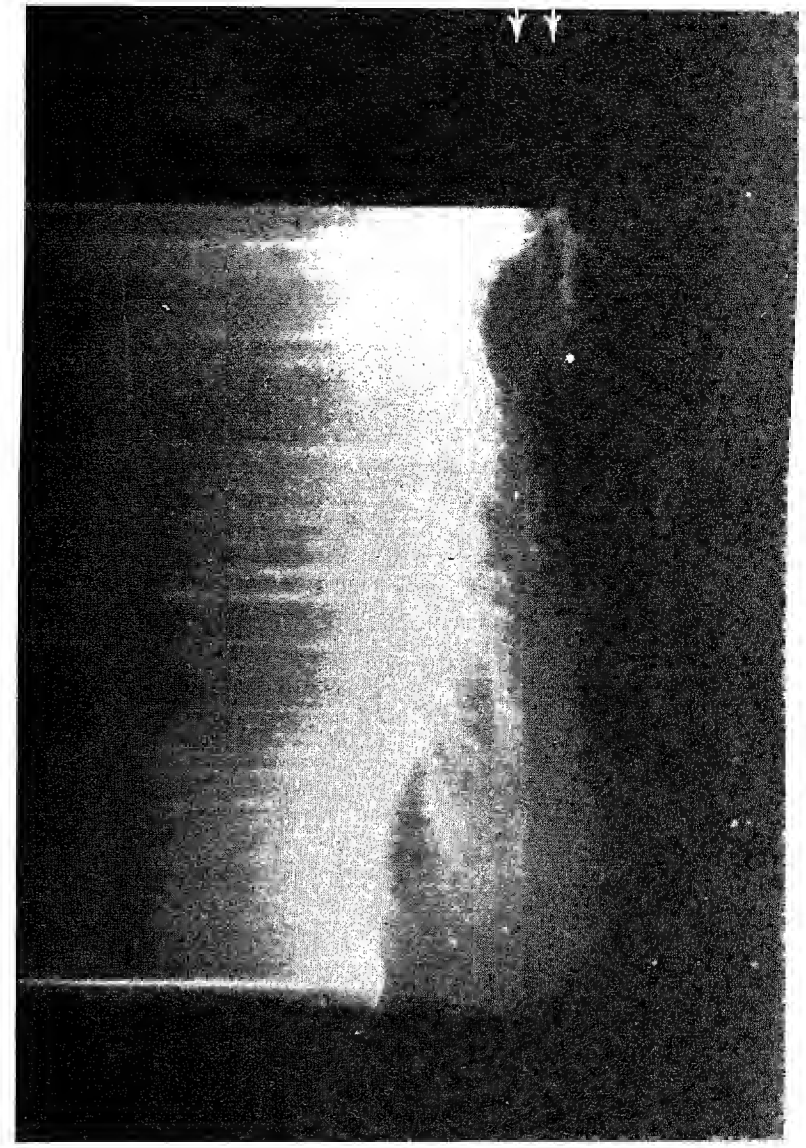


Fig. 10E.—Rotating-camera photograph of impulse-voltage discharge at low pressure: point anode/plane cathode.

Pressure = 42 cm. Hg.
α = leader stroke.
γ = main stroke.
α, γ = 24 microsec.

earth.* Such a negative branched discharge is shown in Fig. 3, and its appearance is so similar to that of a positive branched discharge that clearly spark appearance cannot be taken as a guide to the polarity of the electrode from which the discharge develops. In the case of the lightning discharge it is known that a considerable current flows from earth to the atmosphere beneath a charged cloud, as proved by the appearance of brush discharge from projections on the earth's surface; and so the laboratory conditions relating to Fig. 3 roughly simulate field conditions. The large positive space-charge created above the earthed points directs the approaching discharge from the high-voltage cathode, and causes branching if the positive space-charge is widely distributed. That growth of the discharge takes place in both directions simultaneously (in the laboratory) is shown by the extensive discharge from earth on the right of Fig. 3 and by the upward- and downward-directed finely-branched discharge shrouding the main stroke on the left of Fig. 3. This upward branching at the base of the discharge when the upper portion of the discharge is showing a downward branching has not been observed in the field, but few photographs of lightning show the lower few metres of the flash. An even more notable example of the dual growth of streamers when the high-voltage electrode is negative is given in Fig. 4 (see Plate 2) (the high-voltage negative electrode is a multi-pointed plane of small dimensions: the earthed anode is an extensive uneven plane). In addition to the complete spark on the right of the Figure, there is an incomplete spark on the left composed of a short negative streamer and a long upward-developing positive streamer. This dual growth is referred to later in this Section: its appearance seems to contain a serious obstacle to the existing theory of the lightning discharge. To emphasize the phenomenon a Lichtenberg photograph of a point-plane discharge was taken in a rather unconventional manner: instead of the plane electrode being beneath the photographic plate, the plate was mounted in free space vertically on a horizontal brass plate; and a thin tinfoil pointed electrode was fixed on to the plate 4 in. above the plane. Figs. 5A, 5B, and 5C (see Plate 3) show the form of figures obtained. Fig. 5A, with the point positive, shows the typical positive discharge developing towards the plane. Fig. 5B, with the point negative, shows the typical negative discharge developing from the cathode. Fig. 5C is taken for a very slightly higher (10 %) voltage than for 5B: the diameter of the negative figure has scarcely changed, but arising from the positive plane are long positive streamers terminating on the space charge of the negative figure (the voltage is appreciably below the sparkover voltage), so the analogy with Fig. 4 is very close.

(b) Observations with the Rotating Camera

If the whole of the corona discharge to earth can be seen, even when sparkover occurs, it is obvious that much of the corona must be established in the few microseconds between the application of the field and its removal at the instant of sparking. Even if the gap is paralleled by another gap set to sparkover with a shorter time-lag the corona can still be seen, though it was noticed that the extent of the corona was reduced very roughly in proportion to the reduction in the time-lag. It is to be expected, therefore, that examination of the spark with a rotating camera should distinguish between the start of corona and the main spark. Such a distinction was found by the author* some time ago for both positive and negative discharges, although at that time the photographic conditions only allowed of the corona being photographed for about 20 % of the distance between electrodes, and in this distance it was impossible to detect an approach of the leader stroke to the main stroke with increasing distance from the high-voltage electrode. A typical result is shown in Fig. 6(*a*) (see Plate 4) for a negative point-plane gap, and in Fig. 6(*b*) for a positive point/pointed-plane gap. The measured separations between leader and main stroke agree closely with the measured time-lags of oscillograms of the applied voltage, so that "time-lag" can be identified with time for the initial leader-stroke to bridge the electrodes. The speeds of formation of the leader strokes, calculated from the time-lags, averaged 6×10^6 cm. per sec. for the positive leader and 20×10^6 cm. per sec. for the negative leader. These values corresponded to the minimum impulse sparkover of the gap: with small over-voltages the lags are reduced. It was also discovered that, with negative polarity, a leader discharge formed simultaneously at the earthed electrode if this took the form of a pointed projection above the earthed plane.

Recently the author has had an opportunity of re-investigating the leader-stroke formation in the laboratory with a quartz-lens rotating camera and with a higher-voltage impulse generator. The results confirm and extend the earlier results. The photographs of the leader-stroke discharge show that it extends over the whole inter-electrode gap and forms with the return or main stroke a perfect V-formation typical of the lightning records taken on a rotating camera. Branches on the leader stroke are often followed exactly by branches on the main stroke. The leader-stroke intensity is almost uniform from high-voltage electrode to earth, in marked distinction to the results of the earlier work with the glass lens. A typical leader-stroke is shown in Figs. 7A and 7B (see Plate 5) for a positive point-electrode/negative plane (earthed) together with a lightning leader-stroke recorded by Schonland and Collens.† The leader-stroke formation occurs for positive and for negative impulses, and, as before noted, the time-lags determined oscillographically agree with the time separation of leader and main stroke, the negative lag being much smaller than the positive lag. The negative leader-stroke presents features quite different from the positive leader. It never reaches the earthed electrode. From the earth arise positive leader-strokes to meet the downward leader-stroke; and if from the earthed plane a small pointed projection is raised, the length of the positive leader-stroke is greatly enhanced. A negative discharge is shown in Fig. 8A; the downward-directed leader meets an upward positive leader in mid-gap. In Fig. 8B a pointed projection 2 % of the electrode-spacing in length is raised from the plane, and the leader strokes are seen to meet at 64 % of the gap spacing from the earthed electrode. These results clearly support the type of record shown in Fig. 4,

* T. E. Allibone and B. F. J. Schonland: *Nature*, 1931, vol. 128, p. 794.

* *Loc. cit.*

† B. F. J. Schonland and H. Collens: *Nature*, 1933, vol. 132, p. 407.

of sparks developing towards one another. If a positive high voltage were applied to the type of gap described for Fig. 8B, the positive leader-stroke would still almost completely bridge the gap, and an upward-directed negative leader-stroke (if any) would be very short.

At first the appearance of the leader to the positive discharge* is disconcerting, especially after one has accustomed oneself to the electron avalanche, or dart, theory of the kind suggested by Dorsey† to account for the development of the lightning discharge. Schonland‡ seems to have accepted the view that the leader to the lightning flash is caused by an electron avalanche, and has deduced therefrom that the polarity of the base of the cloud is negative. Now that the positive leader-stroke has been shown to exist—and indeed it is the easier of the two to produce—one may justly question the polarity of the cloud producing the stroke unless other evidence§ is available as to polarity for each stroke, because the appearance of the leader/main-stroke combination cannot now be regarded as a criterion for deducing the cloud polarity. Indeed, this argument can be further advanced. If lightning from a negative cloud is branched, it is because an extensive space-charge shrouds the earth: that is, points project from the earth and contribute their " St. Elmo's fire ": if points do this, they will very likely be the origin of streamers which develop and branch upwards and, when the main flash occurs, upward- and downward-directed leaders as in Figs. 8A and 8B will be revealed by the Boys camera. Since no such leaders have yet been observed, it is suggested that some of the leaders may have developed from positive clouds, unless it is that the camera has not been able to record the path of the discharge near to ground.

There is still considerable evidence that positive lightning-strokes occur in addition to negative, although the latter are more abundant.|| It is important to note that measurements of lightning-stroke polarity on transmission-line towers¶ which result in 97 % of all recorded strokes being of negative polarity give no indication whatever of the distribution of negative in relation to positive strokes in open country. To prove this, the author applied 100 impulses of (i) negative and (ii) positive polarity to a point-plane gap with a point projecting from the earthed plane to a distance of 2 % of the gap spacing (corresponding to a tower 20 m. high under a cloud 1 km. above it). When the projection was beneath the high-voltage point, 100 % of all negative discharges terminated on it, and 80 % of all positive discharges terminated on it. When the projection was displaced from beneath the point by a distance equal to one-third of the gap spacing, 100 % of negative and 5 % of positive discharges terminated on it. Of all discharges striking the projection in this location, 95 % were of negative polarity; thus the point " attracts " the discharge differentially. The 97 % observed negative currents in transmission towers might have originated from an equal preponderance of flashes of the two polarities. This " filtration " of results does not appear to have been realized hitherto. The explanation is, of course, now obvious: from the projection a positive leader develops, as shown in Fig. 8B, and meets the negative leader-stroke somewhere in mid-gap. It is to be expected that Boys-camera records on points such as the New York skyscrapers* will show upward-directed leader-strokes if negatively-charged clouds strike to these buildings.

Although the positive leader cannot be explained by Dorsey's theory its existence is not surprising; because, at voltages just below sparkover, or with chopped impulses, a strong discharge develops from the point electrode in the long gap. It is presumed that the well-known explanation of the positive brush discharge, and positive Lichtenberg figure, holds: the electrons move inwards to the point, the head of the disturbance moves away from the point, and the positive ions remain immobile. The electrons are accelerated inwards at the advancing tip of the discharge and are probably produced by photo-ionization of the gas as described in Section (2). The positive ions left behind advance the electric field from the positive point-electrode towards the plane cathode and thus assist in propagating the discharge even though the average gradient (point-plane) is only 4–5 kV per cm. With negative leader-strokes the electrons proceed away from the high-voltage electrode and leave a positive space-charge which in part neutralizes the field: about twice the average gradient for positive leaders is necessary to propagate negative leaders. The author cannot accept the view of Strigel† that, in the case of the positive-point/plane-cathode, electrons have first to be released from the plane cathode, travel to the anode, and there form a " plasma tube " which extends away from the anode towards the cathode. There is not sufficient time for this to occur. The electrons come *first* from the air in the region of the anode point, travelling and rapidly ionizing towards the anode. The proof of this is that if electrons were to come *from* the cathode plane a time t_1 would first be necessary for their transit to the anode: thereafter another time t_2 would be necessary for the " leader " or avalanche to extend back to the cathode before the main stroke occurred. Now we can show *exactly* that t_2 is the time from application of the voltage to breakdown (more strictly, from somewhere on the rising front of the voltage wave to breakdown; but if the front rises rapidly this time is very accurately measured) and therefore no t_1 time exists, and the first electrons to ionize and to start the downward directed " leader " must arise in the vicinity of the anode, not at the cathode plane.

(c) Detailed analysis of the Positive and Negative Leader-Strokes to the Long Spark

Examination of many records similar to Fig. 7 shows that the leader stroke develops with increasing velocity from anode point to plane cathode. The average speed

* In a private communication, Prof. Schonland has advised the author that he has also obtained positive and negative leader-strokes to the laboratory-produced spark.

† N. E. Dorsey: *Journal of the Franklin Institute*, 1926, vol. 201, p. 485.

‡ *Loc. cit.*

§ Since the author wrote this, a further article by Schonland (*Transactions of the South African Institute of Electrical Engineers*, 1937, vol. 28, p. 204) has given oscillographic proof of cloud polarity: " Those flashes which strike the ground in South Africa are from the negative pole."

|| See G. C. Simpson and F. J. Scrase: *Proceedings of the Royal Society*, A, 1937, vol. 161, p. 309.

¶ W. W. Lewis and C. M. Foust: *General Electric Review*, 1931, vol. 34, p. 452; and H. Grünewald: Paris H.T. Conference, 1935, Paper No. 326.

* The author has recently come across photographs by Shimer, published by Prof. J. C. Jensen (Nebraska) in the *Scientific Monthly* for 1935, showing upward branching from the Empire State Building. Unfortunately the photographs were taken with a stationary camera, so there is no indication of the direction of propagation of the leader stroke.

† *Loc. cit.*

can be controlled by adjusting the circuit constants, and in these experiments is found to be from 2×10^6 to 7×10^6 cm. per microsec. There is a little uncertainty in estimating this, as the speed of propagation of the main stroke has not yet been measured, but this speed will certainly be 10–15 times higher than that of the leader stroke as the oscillogram shows such a rapid collapse of voltage: this uncertainty will shortly be removed, and the results will be published elsewhere.*

Branching of the leader-stroke to the spark is accurately followed by the main stroke, and it will shortly be possible to quote the speed of propagation of the leader down-branches, and to give the full time history of the return stroke. The leader sprays an intense discharge from branches to earth, as in Fig. 4. The separation in time of leader and main stroke at the sharp pointed anode agrees closely with the time-lag as recorded on the oscillogram of the discharge.

Examination of many records similar to Figs. 8A and 8B shows that a leader stroke always develops from the cathode point towards the plane anode: a leader also develops from the anode plane, and, when the two meet, the main stroke extends from this junction in both directions. In front of the negative leader-stroke will be seen a number of pre-discharges which terminate in space and the time-lags recorded on the oscillograms agree with the total time between the occurrence of the first of these pre-discharges and the mainstroke. The speeds of propagation of the upward and downward leaders have not yet been accurately measured, but there is no great difference between them. Examination of the records of the type shown in Fig. 8B reveals similar results to those of Fig. 8A except that the upward-directed positive leaders are longer and more branched.

The time to sparkover of the point-plane gap depends on the wave-shape of the applied impulse, so that it is not surprising that the speed of development of the leader stroke to the spark can be controlled by adjusting the circuit constants—in particular, the series resistance and the load capacitance—and also by varying the degree of over-voltage applied to the gap. In general, the speed of propagation increases as the series resistance of the circuit diminishes, the load capacitance being kept constant. Now a discharge will usually start from the high-voltage electrode at a small fraction—say 10 % of the sparkover voltage of the gap: if the rate of rise of voltage is high, e.g. 1 000 kV per microsec., the tip of the discharge will only have moved forward 10 cm. in 1 microsec. if its speed is 10^7 cm. per sec., by which time the field will have increased tenfold. Under these conditions the discharge might be expected to travel with ever-increasing velocity, and its separation from the main stroke would present difficulties with the present camera. This may explain why the records reported by Allibone and Schonland† only show the leader stroke for a fraction of the gap. If, however, the rate of rise of voltage is small, say 1 000 kV in 20 microsec., and if the starting velocity of the leader is again 10^7 cm. per sec., it is probable that the leader will only develop a short distance from the high-voltage electrode and then cease until the voltage has reached a higher value, when a fresh leader may start out from the electrode. This would result in a step-by-step development of the leader stroke, which is in fact discernible in the records of Figs. 8A and 8B. If this argument is applied to the stepped leader of the lightning flash, we reach the conclusion that the cloud potential at the point of origin of the stroke only rises slowly (at about 100 kV per microsec.). It does so probably because, for the cloud to acquire additional charge, streamers must be propagated from that part of the cloud to the surrounding parts of the cloud, and these streamers only advance with a velocity of the order of 10^7 cm. per sec.

It is of interest to re-examine Strigel's results* in the light of the above work. His available recording speed exceeded the author's, but no leader stroke was observed. He suggests that a leader is distinguishable within 1 mm. (0·84 microsecond) of the main stroke for a 5-metre gap (3·8-metre gap for negative point-plane), giving a leader-stroke speed of 6×10^8 cm. per sec.; but there is a large volume of published data to show that such gaps have far larger time-lags than this, and the most likely explanation of the " area of weaker light impression about 1 mm. wide " is halation from the main spark. The " leader " is probably not recorded because of excessive speed of rotation and slow photographic speed. The absence of oscillographic records of time-to-sparkover prevents an alternative explanation from being given, but the sparkover voltage must have been near to the minimum impulse sparkover voltage, in view of the data on gap-length and applied voltage; and for this, time-lags are probably 20–40 microsec.†

Careful re-examination of the many photographs published by Terada and Nakaya‡ in the light of the above also reveals no trace of true leader-strokes, i.e. ionization from one electrode to the other followed by reverse development of the discharge. The resolving speeds were too low for the gaps used. The pre-discharge shown in the 1929 paper§ is really entirely separate from the succeeding discharge. A large time-interval separates the two, and they are merely of like form, just as successive sparks from a Tesla coil take similar forms due to residual ionization from any one spark leaving a low-resistance path for the succeeding spark.

(4) THE SPARK DISCHARGE IN INHOMOGENEOUS FIELDS AT LOW PRESSURES

(a) Description of Apparatus

With a view to obtaining a better understanding of the mechanism of the long spark at atmospheric pressure, experiments were conducted at pressures below atmospheric. A glass cylinder 36 in. high and 16 in. diameter was fitted with a brass earthed plane electrode and a brass pointed high-voltage electrode spaced 30 in. from the plane. It should be noted that this spacing is large compared with the diameter of the plane and therefore the results are more comparable with those given by

* T. E. Allibone and J. M. Meek: *Proceedings of the Royal Society*, A, 1938, vol. 166, p. 97.

† *Nature*, 1934, vol. 134, p. 736.

* *Loc cit.*

† See H. J. White: *Physical Review*, 1934, vol. 46, p. 99; and P. L. Bellaschi and W. L. Teague: *Transactions of the American I.E.E.*, 1934, vol. 53, p. 1638.

‡ T. Terada and U. Nakaya (and R. Yamamoto): *Scientific Papers of the Institute of Physical and Chemical Research* (Tokyo), 1928–31, vols. 8, 9, 10, and 13 (8 papers).

§ *Scientific papers of the Institute of Physical and Chemical Research* (Tokyo) 1929, vol. 10, p. 43.

point-point electrodes than by a true plane electrode, except when the discharge terminated in the central region of the plane. These details are noted in the description of the results obtained.

The tube ends were sealed with low-vapour-pressure compound and the tube was evacuated by an oil rotary pump. The residual gas would in general be air of normal composition; the chamber was repeatedly filled with air so that no great quantity of hydrogen was likely to have accumulated. The products of combination in the spark were left in the chamber during any one set of experiments, but no change in the character of the discharge which could be ascribed to a changing gas-composition was noticed. No drying reagent was introduced; the original air in the chamber would daily be at average humidity.

More careful experiments in different gases are being performed and will be discussed elsewhere. The experiments were all performed with impulse voltages, and oscillograms were taken of all representative stages of the discharge.

(b) Experimental Results

It is to be expected that at pressures lower than atmospheric the time-lag of sparkover will be greater than at atmospheric pressure. As has been mentioned in Section (2), Dunnington* observed an increase of time-lag with diminished pressure using homogeneous fields. R. R. Wilson† suggests that T varies as $1/\alpha$ and $1/\sqrt{X}$ at one pressure: if pressure variation is considered, then it would appear that T also varies as $1/\sqrt{\lambda}$, where λ is the mean free path of an electron. Thus T varies as $1/p$. It was at once found that time-lags were larger at low pressures than at atmospheric pressure: for positive impulses, with the same circuit-resistance, values of 200 microsec. for a 30-in. gap, instead of 20 microsec., were obtained, and similar results were obtained for negative impulses. The time-lags observed on the oscillograph were in agreement with the separation of the leader from the main stroke to within less than 10 %. The same main phenomenon was observed as at atmospheric pressure: with negative impulses, leaders developed from the earthed plane as well as from the high-voltage point.

The oscillograph proved of great assistance in interpreting the photographic results obtained on the stationary and moving cameras, and vice versa. The breakdown process, which at atmospheric pressure is generally very rapid (the voltage falling abruptly from open-circuit voltage to zero in 10^{-7} sec.) is more complicated at low pressures and takes place in one, two, or more steps, as reported by Tamm,‡ for very short (1- to 5-mm.) gaps in homogeneous fields. As a result of the present experiments, explanations can now be offered for the step in the breakdown records reported by the author§ 4 years ago. The results will be detailed in order of increasing pressure from 1 cm. to 76 cm. of mercury, but more detailed analyses will be published later.

(i) 1 cm. pressure.

Point anode.—A bushel of diffused light extends from anode to cathode, expanding in diameter, as shown in Fig. 9A (see Plate 6). Positive-ion bombardment of the plate cathode causes intense patches of light (copper spectrum) at the cathode.

Point cathode.—A similar bushel extends to the anode: the copper-spectrum patches of light now appear on the cathode rod. Streamers also develop from the plate upwards, as seen in Fig. 9C. No breakdown occurs on the oscillograph unless the ascending and descending streamers meet. With chopped voltages (chopped after 50–100 microsec.) the bushels extend only a short way from the high-voltage electrode.

(ii) 2 to 6 cm. pressure.

Point anode.—The bushel develops a sharply defined core of intense radiation and diminishes in diameter with increasing pressure. The path becomes more tortuous (see Fig. 9B). The rotating camera shows lags of 100 microsec. between the first streamer development and final sparkover, but some microseconds before sparkover occurs a leader is obvious against a large background of corona.

Point cathode.—A core develops at the cathode, and also, in a few records, from the edge of the anode plane upwards. The two discharges meet somewhere in mid-gap: in other records the cathode bushel contracts to a straight sharply-defined core directed to the centre of the anode plane.

Breakdown at these pressures is now apparent on oscillograms and occurs in steps, as reported by Tamm* for very small gaps. When the cathode discharge meets as ascending anode streamer, time-lags are short: when it passes direct to the centre of the anode-plate, time-lags are long (100–200 microsec.).

Fig. 9D shows a negative discharge from the point cathode, meeting a positive discharge from a point on the rim of the anode plane, and this gives a sudden step in the oscillogram.

(iii) 6 to 24 cm. pressure.

Point anode.—From this lower pressure upwards the main discharge is now concentrated, and leaders appear in all rotating-camera records of sparkover: at voltages lower than sparkover the corona contains one or more bright cores which would become the "leaders" to sparkover with a slightly higher voltage. Time-lags are of the order of 30 microsec., and with higher pressures the leader stroke is initiated without any apparent pre-discharge. Fig. 10A (see Plate 7) shows the corona developing from the point at 6 cm. pressure, followed by three leaders, and the main stroke 65 microsec. after the initial corona formation.

Fig. 10B shows the leader at 24 cm. pressure developing from the instant of application of voltage, and in 51 microsec. the main stroke follows from plate to anode point. The leader exhibits much branching, which is not always copied by the main stroke.

Point cathode.—At these pressures almost all discharges show twofold origin—cathode and anode. Fig. 10C (see Plate 8), for 6 cm. pressure, shows the cathode discharge; and from the centre of the anode plate a discharge grows up to meet the cathode streamer. It concentrates to a core similar to the mid-gap streamer investigated by Dunnington,† White,† and von Hippel

* *Loc. cit.* † *Loc. cit.* ‡ *Loc. cit.* § *Loc. cit.*

* *Loc. cit.* † *Loc. cit.*

and Franck,* and then branches again with familiar positive-streamer formation. Sparkover does not immediately ensue: an interval of 108 microsec. elapses. In this interval, many (5 or 6) discharges occur from cathode and anode, but no obvious " leader " of the positive-leader kind develops. At 24 cm. pressure the discharge shows leaders at cathode and anode, that at the cathode being now indistinguishable in form from the positive-leader formation. Fig. 10D shows a good example of this: the time between leader and main stroke at the cathode point is 19 microsec. and at the anode plate is 16·8 microsec. The anode leader shows strong upward branching.

(iv) 24 to 76 cm. pressure.

Point anode.—There is now no further change in type of discharge from that reported at 24 cm. in Fig. 10B. Fig. 10E, at 42 cm. pressure, shows a leader 24 microsec. in front of the main stroke, and the multiple branching results in a shower of corona extending to the earthed plate.

Point cathode.—Unfortunately at these pressures the discharge from anode-plate upwards clung to the glass wall and made the interpretation of photographs difficult. Negative and positive leaders are just distinguishable, but no record at 42 cm. pressure is suitable for reproduction: the results at 76 cm. are to be found in the preceding Section.

(c) Résumé

It is impossible to compare the above results with other records, as no rotating-camera photographs of low-pressure discharges have (to the author's knowledge) been previously taken. Von Hippel and Franck† remark that, at low pressures, electron avalanches no longer suffice for building up space charge, owing to the low value of α. (If X/p is unchanged at low pressures, as seems to be the case down to 6 cm., then α is only of the order of 0·05–0·1, and one electron only produces 100–130 electrons in traversing the whole length of the chamber.)

This seems to be borne out by the fact that no true leader formation is apparent until pressures of 6–20 cm. for a 30-in. electrode gap are attained. This also explains qualitatively why the time-lags are so long, but no quantitative explanation can yet be offered. The simultaneous development of discharge from anode and cathode with point cathode yields the double-stepped type of breakdown on the oscillogram, and there is evidence to show that the anode leader starts some time after the start of the cathode leader (see caption to Fig. 10D). At present, therefore, it would appear that negative discharges do not necessarily propagate themselves more rapidly than positive discharges (as evidenced by time-lag measurements in papers already cited), but that shorter time-lags with negative point electrode may be due to the simultaneous growth of streamers of the kind shown by the stationary camera—in Fig. 4 at atmospheric pressure and in Fig. 10D at partial atmospheric pressure.

* *Loc. cit.*

† *Loc. cit.*

(5) CONCLUSIONS

Study of the long spark reveals that " leader " strokes, of the kind first discovered in the lightning flash by Schonland and others, precede the main spark at atmospheric pressure and at pressures down to $\frac{1}{5}$ atmosphere. From positive point electrode to plane earthed cathode these leader strokes are of a simple nature: from negative point electrode to plane earthed anode the cathode leader is met by a rising anode leader—at least under all circuit conditions so far examined—and if points project from the plane electrode then the anode leader from these points is always present. The leaders branch as they develop, and the main stroke follows the path of the leader and of the branches. The speed of the leader development can be controlled by variation of circuit constants, and since in the lightning flash the charge has to be collected from the raindrops or ice particles in the cloud, the " resistance " within the cloud may be expected to vary over a wide range; this alone would appear to result in a variation of speed of leader propagation, exactly as found in the laboratory experiments described above.

Velocities of leader-stroke propagation are lower than those encountered in the lightning discharge, but further research will be directed to afford a better understanding of the leader-stroke mechanism.

(6) ACKNOWLEDGMENTS

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A THEORY OF FLUCTUATION NOISE

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SUMMARY

From a consideration of the physical phenomena involved in thermionic conduction and in thermal or Johnson noise, it is deduced that the noise in a space-charge-limited valve is best expressed as a thermal noise, and it is shown that a small correction must be applied to the valve slope resistance to give the value of resistance effective as a noise source. The theoretical temperature of this resistance is then shown to be approximately half the cathode temperature. In a temperature-limited valve, both the resistance and the temperature of the conducting path are indeterminate. The "pure shot noise" formulae are applicable to this case, and represent the maximum noise which can result from the passage of a given current through the system. It is incorrect, however, to state that in space-charge-limited conditions "pure shot noise" is smoothed out, while thermal noise in the internal resistance of the valve appears as an additional factor; shot noise and thermal noise in the valve's internal resistance are essentially the same phenomenon, but are modified by the differing conditions of electron transit.

Nyquist's expression for thermal-agitation noise is derived from the atomic mechanism in the case of a metallic conductor.

(1) INTRODUCTION

The author might perhaps be accused of temerity in attempting a theory of such weighty subjects as shot noise and thermal-agitation noise without having the backing of any experimental work; but from discussion with workers in this field there seemed to be scope for one with training as a physicist to endeavour to interpret the results of other radio workers, even though statisticians regard the problem as unpromising. Those who are familiar with the subject are asked to forgive the elementary treatment of simple shot noise with which the paper opens; it is included because it appears to be an appropriate starting point in the search for a coherent theory based on fundamental principles.

Although in the realm of mechanical engineering we do not find the atomic structure of matter forcibly brought to our notice, yet in electrical technique we have already reached the stage where the discrete nature of the electric current is clearly perceptible. As an extreme instance of the sensitivity attainable by thermionic-valve methods, an electrometer valve can be made to detect a current of the order of 10^{-18} ampere—say 10 electrons per second. If the indicating system could be made of sufficiently short time-constant, such a current would necessarily be found to be non-uniform, but other information is required to predict whether the variation will be a regular $0\cdot1$-second cycle, or an irregular distribution subject only to the constancy of the long-period mean. (Actually, these minute currents can at present be measured only by a condenser-charging method, so we are very far from the required rapid indicating system which would give the direct experimental answer to this question.) Considering only electron currents (i.e. disregarding any phenomena such as electrolysis or gas discharge, which depend in part on conduction by heavier ions) we may distinguish between electrons travelling within a conductor and those travelling through free space; in the problem of valve noise we are concerned with the latter category. Now electrons may be emitted from conductors into space by various mechanisms—radio-activity, thermal emission, photo-electric emission, and ionic or electronic bombardment (the last including secondary emission). Atomic physics shows that all these processes are essentially "random," meaning that although it is possible to predict the mean value of any quantity involved, from statistical laws based on previous observations of large numbers of events—just as actuaries will determine a statistical value for the length of life of any class of persons—yet the behaviour of the individual unit, when we come down to atomic phenomena, is as incalculable as the life of an individual human being.

It is reasonable to assume, therefore, that the electrons constituting the currents in a thermionic valve are emitted at random times. Suppose, then, that five different currents, each having a mean value of 10 electrons per second, could be observed for 2 seconds, and that the 20 electrons in each were found to be distributed over the 2 seconds in the manner represented by the curves lettered A, B, C, D, E, in Fig. 1, where the 2-second period has been divided into intervals of 1/10th second. In each current the mean number of electrons is 1 per $0\cdot1$-second interval, but the individual values vary between 0 and 4 electrons per interval; while adding all five currents together, giving a mean value of 5 electrons per $0\cdot1$ second, is seen from the curve marked "Sum" to produce variations from 2 to 12. Although this diagram has not, of course, any great quantitative significance,* it clearly illustrates that as the number of electrons with which we are dealing becomes greater (i.e. the current is increased) the rate of flow becomes *relatively* smoother, but the *absolute value* of the variations is larger. Thus, on the one hand, large currents are for ordinary purposes regarded as

* The random distributions of Fig. 1 were obtained by drawing lots as follows. Cards numbered 1 to 20, corresponding to the 20 intervals of the period plotted, were shuffled and draws were then taken at random; after noting the number each card was replaced and shuffled, the process being repeated until 100 numbers had been drawn. The first 20 of these numbers, in order of drawing, were taken to represent the numbers of those intervals of the period during which an electron passed for current A, and successive batches of 20 for the other currents. The number of electrons attributed to the nth interval of $0\cdot1$ second is thus equal to the number of occasions on which a card numbered n was drawn during the 20 draws representing the particular current. The result should be genuinely "random."

uniform, while on the other hand the shot noise in a temperature-limited valve increases in proportion to the current. If in a wireless receiver the steady current of the valve in each stage of amplification were in proportion to the signal strength, so that the anode current in each valve was approximately 100 % modulated by a strong signal, this type of phenomenon would still cause a deterioration of signal/noise ratio as the sensitivity was raised, since the smaller currents in the input circuit would then be subject to a large relative fluctuation; this corresponds to the case of a photocell combined with an electron-multiplier. The increase of

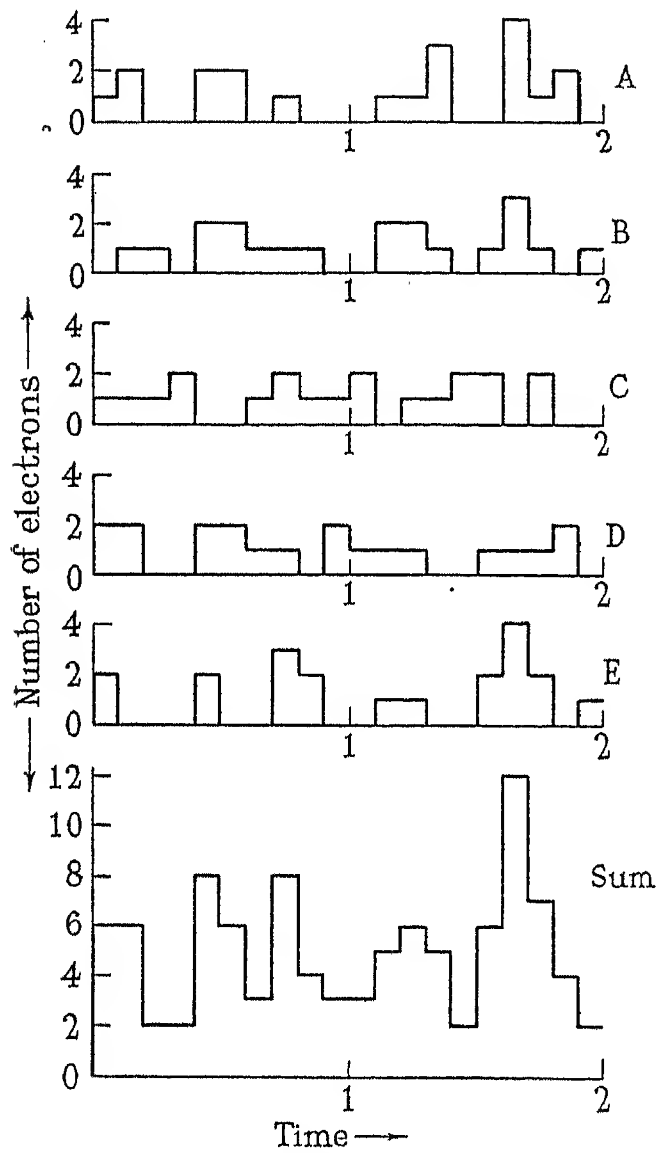

Fig. 1

noise here arises from the fact that with decreasing signal amplitude the charge conveyed across a valve per half-cycle of signal current is becoming more comparable with the charge on a single electron. But in a normal amplifier one might expect a far worse state of affairs, since the current in the first valve depends upon the type chosen, and the size of valve cannot be indefinitely reduced in proportion to the signal strength. Actually, however, the ordinary thermionic amplifying valve works under conditions of space-charge limitation (not temperature limitation), and it is known that the valve noise is then less than predicted by the simple shot-noise theories. The noise in the presence of space-charge limitation is discussed later in this paper.

(2) TEMPERATURE-LIMITED CONDITIONS

Existing theories, which are well supported by experimental results in the temperature-limited regime, show that the mean square of fluctuation voltage at the anode of a temperature-limited diode is directly proportional to the magnitude of the current from which it arises. Moullin and Ellis,* for example, give the formula

$$V_s^2 = I_{av.}eR/(2C) \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where V_s^2 is the mean-square shot voltage in an anode circuit, having resistance R shunted by capacitance C, connected to a diode having temperature-limited anode current of mean value $I_{av.}$. For an oscillatory anode circuit they give

$$V_s^2 = \frac{I_{av.}eL}{2RC^2}(1 + F^2) \quad . \quad . \quad . \quad . \quad (2)$$

where $F = R/(\omega_0 L)$. Now for a good tuned circuit $R/(\omega_0 L)$ at resonance ($\omega_0 = 2\pi$ times the resonant frequency) is of the order of 10^{-2}, so that F^2 is negligible compared with unity. Writing $L/(RC)$, the dynamic resistance of the circuit, as R', the formula for noise in a tuned circuit becomes

$$V_s^2 = I_{av.}eR'/(2C) \quad . \quad . \quad . \quad . \quad (3)$$

which is of the same form as (1), but employing the dynamic resistance of the circuit in place of an ohmic resistance. It is interesting to note that in (3) the factor C still appears in the denominator. This suggests that the use of a tuned circuit of low L/C ratio with low resistance will give the best signal/noise ratio for a given amplification, i.e. for constant value of the dynamic resistance R'. However, this policy is limited firstly by the difficulty of lowering the resistance sufficiently to maintain the desired value of dynamic resistance, and secondly by the increasing selectivity which results from the small decrement and tends to limit the band-width. It may be said, in fact, that the reduction of noise has been obtained at the expense of decreasing the band-width.

(3) SPACE-CHARGE-LIMITED CONDITIONS

So far we have only mentioned conditions covered by equation (1), which is based on the assumption that the time of transit of the electrons is so small as to have no effect on the noise spectrum, and that the arrival of electrons at the valve anode is "random," i.e. that the emission of an electron is not influenced by the time at which any previous electron was emitted, or arrived at the anode, but is controlled solely by the combination of the external electric field (due to potentials on the various electrodes of the valve) and its own energy of thermal agitation within the cathode. Experimental results support this equation for temperature-limited conditions; but when there is sufficient surplus emission to form a considerable space-charge it is found that the noise is substantially reduced. Indeed, the existence of a finite anode-slope resistance shows that the charge on the anode (which is dependent upon the number of electrons that have previously arrived there) must have some influence on the adventures of electrons emitted

* See Reference (1).

at a later time, and therefore casts some superficial doubt on the hypothesis of truly random emission.

It is generally agreed that with this space-charge (which is after all the practical working condition in some part of the electrode system of every amplifying valve) the envelope of noise voltage, i.e. the larger fluctuations arising from the random arrivals of numerous electrons, as illustrated in Fig. 1, must produce an opposite fluctuation in anode current, just as much as would occur with any signal voltage developed across the external circuit and appearing as a potential on the anode. (The noise envelope is of course a function of the characteristics of the external anode circuit, as well as of the fluctuation in the current arriving at the anode.) If then the valve has slope resistance R_a and the external circuit is as assumed for equation (1), this effect is believed to cause a reduction in the shot-noise energy by a factor $R_a/(R_a + R)$, giving the Moullin and Ellis equations

$$V_s^2 = \frac{1}{2}I_{av.}e\left(\frac{R_a}{R_a + R}\right)\frac{R}{C} \quad . \quad . \quad . \quad . \quad (4)$$

for the total noise voltage, and

$$V_{df}^2 = 2I_{av.}e\left(\frac{R_aR}{R_a + R}\right)^2 df \quad . \quad . \quad . \quad (5)$$

for the noise voltage in a narrow band of frequencies df. For lack of a better name, the theory represented by equations (1) to (5) will be referred to as the " pure shot " theory, which does not explicitly consider events taking place within the space-charge, but only the arrival of electrons at the anode. According to this view, shot noise is as a first approximation expressible solely in terms of the magnitude of the current arriving at the anode [equation (1)]; after allowing for the effect of external-circuit characteristics and internal resistance of the valve on the voltage actually generated on the anode [equations (4) and (5)], any corrections required under space-charge conditions are outside the scope of this theory. Actually, however, it is agreed by all experimenters that valve noise is greatly reduced, but never completely abolished, by space-charge limitation of the anode current.

Llewellyn* and a number of American workers, on the other hand, take an entirely different view, leading to what may be briefly described as the " thermal noise plus shot noise " theory. They consider that there are two separate sources of noise within the valve. First, random emission from the cathode in the temperature-limited condition must cause an exactly corresponding random arrival at the anode, and hence give rise to " pure shot noise." But Llewellyn considers that when space-charge is present it smooths out the random emission from the cathode, so that arrival at the anode is no longer random, the smoothing being proportional to a factor $(dI/dI_c)^2$; the pure shot noise is to be multiplied by this factor to give the shot noise modified by space-charge. (I is the actual anode current, and I_c the total emission from the cathode.) Thus with complete space-charge limitation, $dI/dI_c = 0$, shot noise should vanish. But in addition to pure shot noise there is said to be " thermal noise " within the valve, for it is argued that since the valve has an effective slope resistance R_a it must on general grounds of thermodynamics give rise to the amount of thermal-agitation noise (or " Johnson noise ") appropriate to such a resistance.

* See Reference (2).

Experimentally, neither theory has proved satisfactory. The difficulty with the thermal-noise-plus-shot-noise theory has been that in order to correspond to the observed values of slope resistance and noise the temperature of the internal resistance must be somewhere about one-half of the cathode temperature; it has in the past seemed a natural assumption that the slope resistance should be at a temperature equal to that of the cathode, but no published paper has covered this question adequately.* The value of the total emission I_c for use in the factor dI/dI_c is also a matter of some difficulty, not only with dull emitters but apparently even with pure tungsten cathodes. Pearson, for example, published some experimental results in support of the thermal-noise-plus-shot-noise theory against the pure shot-noise theory.† He found it necessary to resort to an extrapolation method to eliminate the effects of external field on the temperature-limited emission from his tungsten cathode; even so, at very small currents (low filament heating) his values of I_c were subject to inaccuracy, for he obtained in the worst case $dI/dI_c = 1{\cdot}03$, i.e. the current to the anode increasing 3 % faster than the reputed total emission from the cathode. The exponents of the pure-shot-noise theory, on the other hand, have not produced any alternative theory for the reduction of shot noise by space-charge.

(4) THERMAL NOISE IN A VALVE

The present author was therefore faced with the problem of first finding the weaknesses and strengths of the two theories referred to above, and then endeavouring to construct a more adequate hypothesis. As regards thermal noise, the author is sufficient of a physicist by training to regard thermodynamics, when properly applied, as an infallible instrument; there appears to be no flaw in Nyquist's thermodynamic proof of the universality of thermal-agitation noise, whatever may be the magnitude of such noise.‡ Moullin objects that within the valve there is no collision between free electrons and fixed molecules, so that, the mechanism of ordinary resistance being absent, thermal agitation noise which arises in solid conductors should also be absent.§ But consider a resistance connected between grid and cathode of an amplifying valve; thermal noise arising from this resistance is apparent only as a varying charge on the grid of the valve, and, though we may fairly deduce therefrom that there is a random motion of electrons in the resistance, we need independent evidence to determine how that random motion is caused. Similarly, if the electrons within the anode stream of a valve have random components of velocity, they can produce a " noise " voltage which is indistinguishable from that

* A paper on this question by B. J. Thompson and D. O. North was presented at the Rochester meeting of the Institute of Radio Engineers, 16th November, 1936, but so far as the author is aware this has only been printed in abstract form.

† See Reference (3).

‡ See Reference (4). An alternative to Nyquist's derivation of the magnitude and temperature dependence of thermal-agitation noise is given at the end of this paper.

§ See Reference (1).

produced by a metallic resistance, though the mechanism of collision with fixed molecules is not present; we have to rely upon the thermodynamic proof, however, to assure us that the relation between magnitude of noise voltage and magnitude and temperature of resistance is the same in both cases. Actually some correction will be required, since a valve is not a true ohmic resistance but has a curved characteristic. Nyquist's argument is based on the power absorbed, which, when a voltage V is applied to a resistance R, is equal to V^2/R; bearing this in mind, we can find the relation between slope resistance R_a (i.e. tangent to the characteristic) and the value of resistance R' effective for thermal noise in any particular shape of characteristic. For example, if the characteristic is

$$i = aV^{3/2} \quad \ldots\ldots \quad (6)$$

the power may be expressed as

$$P = iV = aV^{5/2} \quad \ldots\ldots \quad (7)$$

To find the additional power absorbed when a small extra voltage, e.g. a "noise" voltage, is superimposed upon the mean applied voltage V, equation (7) is differentiated. Thus

$$\frac{dP}{dV} = \frac{5}{2}aV^{3/2} \quad \ldots\ldots \quad (8)$$

Now for a true ohmic resistance of value R' we have

$$P = V^2/R'$$

$$dP/dV = 2V/R' \quad \ldots\ldots \quad (9)$$

We therefore adopt as the definition of the value R' of resistance effective for thermal noise in any circuit element, the expression derived from (9),

$$R' = 2V\Big/\frac{dP}{dV} \quad \ldots\ldots \quad (10)$$

For the 3/2-power characteristic, therefore, we find from (8) and (10) that

$$R' = \frac{2V}{(5/2)aV^{3/2}} \quad \ldots\ldots \quad (11)$$

This is related to the slope resistance R_a by writing

$$\frac{1}{R_a} = \frac{di}{dV} = \frac{3}{2}aV^{\frac{1}{2}} \quad \ldots\ldots \quad (12)$$

so that combining (11) and (12) we have

$$R' = 6R_a/5 \quad \ldots\ldots \quad (13)$$

Another important characteristic is the 5/2-power law:—

$$i = aV^{5/2} \quad \ldots\ldots \quad (14)$$

$$P = aV^{7/2} \quad \ldots\ldots \quad (15)$$

$$\frac{dP}{dV} = \frac{7}{2}aV^{5/2} \quad \ldots\ldots \quad (16)$$

$$R' = 2V\Big/\frac{dP}{dV} = \frac{4}{7}\cdot\frac{1}{aV^{3/2}} \quad \ldots\ldots \quad (17)$$

But $$1/R_a = \frac{5}{2}aV^{3/2}$$

Therefore $$R' = \frac{10}{7}R_a \quad \ldots\ldots \quad (18)$$

The third characteristic of practical interest is exponential:—

$$i = ae^{bV} \quad \ldots\ldots \quad (19)$$

$$1/R_a = abe^{bV}$$

$$P = aVe^{bV}$$

$$dP/dV = ae^{bV}(1 + bV) \quad \ldots\ldots \quad (20)$$

$$R' = \frac{2bVR_a}{1 + bV} \quad \ldots\ldots \quad (21)$$

It will be noticed that in all these cases the value of R' is *greater* than R_a, so that the thermal noise from a valve of slope resistance R_a is slightly greater than from an ohmic resistance of value R_a. Alternatively, if the temperature of the valve's internal resistance is calculated from the observed noise voltage and the value of R_a (in place of the correct value R'), the temperature so deduced will be *higher* than the true temperature by a factor such as 6/5 or 10/7.

(5) "PURE SHOT NOISE" THEORY

The next question is whether there is in addition to thermal noise a separate shot noise; the author believes there is not. Thermodynamic reasoning, as usual, indicates the overall relations between the valve, regarded as one unit, and the external circuit, without revealing the internal mechanism within the valve. The random arrival of electrons at the anode, in other words "shot noise," is the expression of the fact that the electrons have a certain random component of velocity which represents the thermal agitation of the electrons, and must therefore be related to thermal noise. It will be shown later in this paper that a proper consideration of the temperature of the valve's internal resistance makes it possible to unify these two aspects of the phenomenon. But, if so, what of the pure shot equation [equation (1) above] for which Moullin states that the sole condition for shot-noise power to be proportional to the magnitude of the mean anode current is that the arrivals of all electrons shall be random? On this view, the noise does not depend upon the magnitudes of the random components of electron velocities, i.e. the temperature of the electrons, but only on the absolute independence of the events constituted by the arrivals of the several electrons at the anode; and the general statement made by some writers that the space-charge "smooths out the irregularities of the emitted current" is unsatisfactory, since it can be shown that space-charge does not destroy the random nature of the electron emission from the virtual cathode.

Moreover, a direct antithesis to the frequency-spectrum method employed in Moullin's derivation of equation (1) is provided by the work of T. C. Fry.* Fry denies the existence of a frequency spectrum of shot noise, and states that "If electrons have been emitted in a statistically steady stream for infinite time past, the probability of the spectrum corresponding to this emission having any pre-assigned ordinate at any given frequency

* See Reference (5).

is zero, and the probability that the ordinate exceeds any finite quantity, however large, is unity." This claims to rule out any derivation in terms of a spectrum determined solely by the number of electrons emitted. But examination of the two papers (Fry's and Moullin's) reveals the critical point at which their analyses diverge to such opposite conclusions. Both authors find a Fourier integral representing the pulse produced by the passage of a single electron from cathode to anode, in which the shape of pulse does not affect those frequencies whose period is large compared with the time of transit of the electron, i.e. the frequencies which are of interest for normal radio work; they then proceed to sum the effect of a large number of electrons arriving in random phase, and the crux of the question is the length of period over which the summation is to extend. Fry sums over an *infinite* period, and hence finds that the resultant for any frequency is infinite, being the sum of an infinite number of vectors of equal magnitude but random phase. In corroboration of this result, Fry quotes Einstein's equation for the Brownian motion as a parallel case where the sum of a number of vectors in random phase tends to an infinite resultant as the number of vectors tends to infinity. Moullin, on the contrary, sums over a *finite* period such that N electrons have passed, and quotes a statistical theorem that the sum of N equal vectors in random phase is equal to $N^{\frac{1}{2}}$ times the magnitude of each single constituent vector. The present author believes that the period of summation should be finite and related to the time-constant of the apparatus used to measure the noise voltages; the time-constant in question should probably be that of the first integrating element in the amplifying and measuring chain, the nature of which naturally depends upon the actual apparatus in use. This rules out Fry's result, but does not thereby justify Moullin's: it remains to be determined whether the period of the summation is in fact such that the statistical theorem which he quotes is applicable.

There seems to be some doubt among statisticians as to the significance of any limiting value of a property of a collection of events which are unlimited in number. (See, for example, N. Campbell's paper on "The Statistical Theory of Errors,"* particularly pages 802 and 803 of that paper.) The problem is, that if ϵ is the deviation of the actual sum of a particular collection of N unit vectors in random phase, from the statistical value of $N^{\frac{1}{2}}$, how large must N be in order that the probability of exceeding a tolerable limit of error ϵ_0 shall be less than a chosen small quantity δ? This is a complicated question, since it involves firstly the *limit of error* ϵ_0 which can be tolerated, and secondly the *probability* δ of exceeding this limit, which shall for practical purposes be regarded as zero probability. That N can be sufficiently large in atomic phenomena for the difference between actual and statistical values to be imperceptible is evidenced by the successful treatment of ordinary liquids and gases in bulk as continuous fluids. A recent paper by E. N. Rowland† discusses the problem mathematically. Taking the case of random distribution of events governed solely by a constant probability (this corresponds to what was rather loosely described as "constant mean current" in connection with Fig. 1), and supposing observations to be made of the resultant effects of numbers of these events occurring in a series of limited intervals of time, the problem considered by Rowland is whether any meaning can be attached to the mean value of the resultant effect averaged over infinite time, and, if so, whether it can be related to the averages obtained over finite intervals of time. He concludes that, provided the intervals of observation are sufficiently long, we may take the mean value found in any single interval of observation as a reasonable physical estimate of the corresponding quantity averaged over all time. He does not, however, give a criterion of the time which is sufficiently long, nor the corresponding tolerance of error implied by the term "reasonable physical estimate." In the terms in which the problem was stated above, Rowland's paper gives rigorous proof of the experimental deduction from the kinetic theory of fluids, that as N tends to infinity, ϵ_0 and δ tend to zero; but it does not give the numerical relation between the three quantities for values of N other than infinity. The "spectrum" derivation of equation (1) is therefore left as of unknown quantitative accuracy but at least qualitatively correct;* it fails to explain the reduction of noise by space-charge, but it may be that this is due to a misunderstanding of the event constituting the unit vector under conditions of space-charge.

* See Reference (6).

† *Ibid.*, (7).

* This is, of course, assuming the validity of Rowland's analysis, which the present author is not competent to question.

(6) PHYSICAL CONSIDERATIONS

As an introduction to an alternative method of calculation, let us return to Fry's paper, and adopt his definition that "The Schroteffekt will be measured by the difference between the energy actually dissipated in the circuit and the energy that would be dissipated if the electron stream were a uniform flow of a continuous fluid." By calculating the energy that would be dissipated in the attached circuit for a single electronic charge instantaneously transferred from cathode to anode of the valve, he deduces the expression

$$W = \nu \overline{W}_1 + W_0 \quad . \quad . \quad . \quad . \quad (22)$$

where W is the total energy dissipated in the circuit, W_0 the steady-current energy, ν the number of electrons emitted, and $\overline{W}_1$ the mean over all electrons of the energy which would be dissipated in the anode circuit on the emission of a single electron. The noise energy is then $\nu \overline{W}_1$.

Before proceeding further, it is necessary to deal with the doubt, expressed by Fry, whether the disturbance to the external circuit caused by the arrival of a single electron can obey the same laws as the disturbance due to a large charge; for example, how can the charge on a condenser decay exponentially if that charge consists only of a single indivisible electron? This problem was also considered by Rowland, who calculated the shot noise in a circuit connected to a temperature-limited diode according to two different hypotheses: (*a*) the electrons arrive and depart suddenly from the anode, having a random distribution of length of life on the

anode, subject only to the half-life constant being such as to give the correct mean value of current; or (*b*) the charge on the anode due to each electron decays exponentially, just as a charge consisting of numerous electrons would. He is surprised to find that it is hypothesis (*b*) which gives the result in accordance with the experimentally verified equation (1). But if one regards the electromagnetic field as the ultimate reality, as in Poynting's theorem for example, this is a reasonable result. The quantum of electromagnetic energy of radio frequencies is so small that the electromagnetic field may here be regarded as continuous. The unit charge remains undivided, but the effective charge on the anode gradually decreases as the electron recedes from it.

Returning to equation (22), let us consider the general conservation of energy in the system comprising the valve, anode circuit, d.c. anode supply source, and hot cathode. The d.c. anode supply is not likely to be the source of the noise energy, which is made up of alternating voltages; it might be argued that the random nature of the emission would modulate the steady anode current and thereby enable some of the energy supplied by the battery to be converted to a.c. energy, but one would then expect the noise energy to be proportional to the energy in the steady current. This is not supported by experiment, for the noise energy in a temperature-limited diode depends only on the anode current, and not on the anode voltage; it therefore seems reasonable to suppose that the energy supplied by the battery is always W, the same as would be expended if the current flow were uniform and continuous. The remaining energy $\nu\overline{W}_1$ involves the mean of a number of energies W_1, each of which is characteristic of some individual electron, not of the external circuit or applied voltages; and the most obvious form of energy which is peculiar to every particle of atomic dimensions is thermal energy. It is therefore a plausible hypothesis to suggest that $\nu\overline{W}_1$ is the thermal energy of the electron stream constituting the anode current; it is therefore a function of the temperature of the virtual conductor (or resistance) within the valve. The shot-noise energy is therefore derived from the random component of kinetic energy (i.e. the thermal energy) of the electrons in the anode-current stream, which in turn is derived from the thermal energy of the cathode. Yet despite the obvious suggestion of a "thermal" energy in W_1, Fry finally deduces for the noise energy in a circuit attached to a valve an expression which is a function only of current, and not of any value of energy associated with the electrons constituting the current.

The reason is that he assumed the *instantaneous* passage of each electron from cathode to anode, whereas the only way in which the thermal-agitation energy of the electrons can make itself felt is in variation of the velocity of the electrons between the valve electrodes, a possibility which is excluded by the assumption of instantaneous transit, since this implies that all electrons alike have infinite velocity.

As a purely qualitative example of the effect of transit velocity on the resultant energy expended in the circuit, consider Fig. 2, where C represents the capacitance between the anode and cathode of a valve, and the resistance R the external circuit. If now charge q is transferred from plate "a" to plate "b" of condenser C instantaneously, the energy introduced into C, and afterwards dissipated in R, is $q^2/(2C)$. Now let the charge be transferred from "a" to "b" over a finite time, according to the following rather artificial hypothesis. First a charge $\frac{1}{2}q$ is transferred instantaneously, charging C to a potential $q/(2C)$, then a current flows such as to maintain this potential difference across R until the remaining $\frac{1}{2}q$ has passed. The energy associated with the initial instantaneous transfer of $\frac{1}{2}q$ is $q^2/(8C)$, and will be dissipated at the end of the cycle of operations, when the condenser discharges from potential $q/(2C)$ to zero. The current required in the second stage

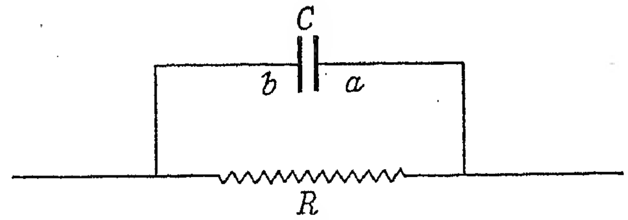

Fig. 2

is $i = q/(2CR)$ [since it is required to maintain a potential $q/(2C)$ across the resistance R] so that the energy dissipated by this current is

$$i^2Rt = q^2t/(4C^2R) \quad . \quad . \quad . \quad . \quad (23)$$

where t is the time of current-flow and is given by

$$t = q/(2i) = (q/2)\,(2CR/q) = CR$$

Therefore $$i^2Rt = q^2/(4C) \quad . \quad . \quad . \quad . \quad (24)$$

The total energy in the cycle of operations is $q^2/(4C) + q^2/(8C) = 3q^2/(8C)$, against $q^2/(2C)$ for instantaneous transit. Thus the electronic velocity of transit should influence the energy dissipated in the external circuit, and the noise energy as calculated by Moullin and Fry on the assumption of instantaneous transit should be a maximum value. This appears to be in general accord with experimental evidence.

It might at first be thought from the above that the reduction of noise in the presence of space charge is due to the increased time of transit of the electrons from cathode to anode; but this is not so, for the time of transit under normal working conditions is short—Moullin (*loc. cit.*) quotes 10^{-9} second—so that the idea of instantaneous transit would be justified on this score. But there is another way of regarding the problem. For example, consider a hypothetical valve in which the electrons are emitted *regularly*, and in such numbers that their periodicity corresponds to a frequency much higher than can be detected by radio apparatus; such a valve would give zero noise, however long or short the transit time of the electrons, for the *regular* wave-form could only produce frequencies above the range of the apparatus, whatever the shape of the constituent pulses of the wave-form. Next imagine a single gas molecule or similar body to be projected across the direction of the current flow, and stop one or two electrons by collision. The stoppage of these electrons will cause a minute pulse to be superimposed upon the steady

current-flow in the external circuit, i.e. will give rise to "noise." From this example we see that deviations of electron velocities from a mean value can cause noise, and we must therefore regard the velocities of the electrons in any space-charge-limited valve as made up of two components:—

(a) All the electrons have an equal mean velocity, corresponding to the observed steady current, and if they had no other component of velocity the noise would be zero in a practical circuit.

(b) Each electron has an individual random velocity of thermal energy, the magnitude of which controls the amount of noise arising in the circuit connected to the valve.

Temperature-limited valves, on the other hand, and any valves whose electrode systems are such that they behave in a similar way, cannot conveniently be regarded from this point of view; for it will be realized from the investigation that follows that it is not possible to assign a temperature to the anode stream of a temperature-limited valve, and in the absence of space-charge there is no significance to be attached to the "mean velocity" shared by all electrons.

(7) TEMPERATURE OF THE ANODE CURRENT STREAM

Earlier in this paper it was stated that a valve which can behave as a resistance must for thermodynamic reasons be a source of noise energy of magnitude appropriate to its resistance and temperature. But it was pointed out that corrections are necessary when the conducting path does not obey Ohm's law, a caveat which applies very strongly, for example, to the temperature-limited diode whose "resistance" is infinite but noise energy finite. It has now been suggested that the source of the noise energy is the random motion of the electrons during their flow from cathode to anode; this is practically identical with the mechanism of thermal noise in metallic conductors.* Since it is thus fair to regard fluctuation noise in a valve having a finite resistance as a thermal effect, it is necessary to find the effective temperature of the electrons constituting the valve's anode current, i.e. the temperature of the valve's resistance.

"Temperature" must first be defined. It is a statistical property of a collection of particles, proportional to the average kinetic energy of random motion possessed by the constituent particles. The term "random motion" is intended to exclude the kinetic energy due to any velocity common to all the constituent particles. Thus a quantity of gas flowing through a pipe at high speed gains additional kinetic energy by its flow, but this does not constitute an increase of temperature, neither does the mean velocity of an electron stream from cathode to anode under the influence of an external source of e.m.f. add to the temperature of the electrons.

O. W. Richardson† showed by thermodynamic reasoning that electrons emitted from and in equilibrium with a hot conductor have a Maxwellian distribution of velocities corresponding to the same temperature as the conductor; he also found this to be in agreement with experimental evidence. It appears that this hypothesis still stands, for Hume Rothery in his book ("The Metallic State," pp. 142–3) states that "within the limits of the experimental methods the electrons emitted from pure metals in a high vacuum have velocities in accordance with the Maxwell law. . . ." It seems certain that if any two systems are capable of exchanging thermal energy, they will in equilibrium be at the same temperature. Such exchange of energy is possible between a hot conductor and electrons surrounding it, by means of both emission and absorption of electrons and reflection at the surface of the conductor.

In a thermionic valve working with a fair amount of space-charge limitation there will be a potential minimum at some point close to the cathode; all space-charge between this and the cathode has a free exchange with the cathode and is therefore at the same temperature. But the passage across the boundary line formed by the potential minimum is an irreversible process: any electron which passes this dividing line is inevitably swept across to the anode. There is therefore no thermal exchange between the cathode and the electrons between potential minimum and anode, and the temperature of these electrons might therefore differ from that of the cathode, and must now be calculated.

From the point of view of noise voltage generated in the external circuit, we are concerned only with electron velocities in the direction of the cathode-anode current stream, and therefore take the components of electron velocity normal to the cathode. This component of the energy of an electron in the outer space-charge* is that with which it left the cathode, less the energy required to pass through the potential minimum, and electrons which are received at the anode are those whose initial velocity component normal to the cathode was greater than was necessary to pass the potential minimum. Richardson (*loc. cit.*) gives the law of distribution of velocities normal to the cathode as

$$N_u du = N \,.\, 2hmue^{-hmu^2} du \quad . \quad . \quad . \quad (25)$$

where N_u is the number of electrons out of a total N which have velocities between u and $(u + du)$, and $1/h = 2kT$. The mean energy of normal components averaged over all electrons leaving the cathode is thus $1/(2h) = kT$. The kinetic energy associated with any group $N_u du$ of electrons is, from (25),

$$W_u = \tfrac{1}{2}mu^2 N_u du = Nhm^2 u^3 e^{-hmu^2} du \quad . \quad (26)$$

Let u_0 be the velocity which is just sufficient to bring an electron to the potential minimum. Then those electrons which pass over to the anode had initially an aggregate energy W_0 given by

$$W_0 = Nhm^2 \int_{u=u_0}^{u=\infty} u^3 e^{-hmu^2} du \quad . \quad . \quad . \quad (27)$$

* The difference is that in a metallic conductor the electrons are in thermal equilibrium with the molecules of the conductor, so that their temperature can be measured by any normal thermometer; in parts of the space-charge, on the other hand, there is no thermal equilibrium between electrons and molecular matter, so their temperature must be calculated from their history since leaving a body having a measurable temperature (i.e. the cathode).

† See Reference (8).

* "Outer space-charge" is a convenient name for space-charge outside the potential minimum.

The number N_0 of electrons passing the barrier is obtained by integrating (25). Thus

$$N_0 = 2hNm\int_{u=u_0}^{u=\infty} ue^{-hmu^2}du \quad . \quad . \quad . \quad (28)$$

$$= Ne^{-hmu_0^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Evaluation of the integral in (27) gives

$$W_0 = \tfrac{1}{2}Nme^{-hmu_0^2}\left[u_0^2 + 1/(mh)\right] \quad . \quad . \quad (30)$$

and on dividing (30) by (29) the mean initial energy of forward velocity of those electrons which ultimately pass the barrier is

$$\overline{W}_0 = \frac{W_0}{N_0} = \tfrac{1}{2}m\left[u_0^2 + 1/(mh)\right] \quad . \quad . \quad (31)$$

But each electron loses energy $\frac{1}{2}mu_0^2$ in passing the potential minimum, since u_0 was defined as the critical velocity. Therefore the average energy $\overline{W}$ of the electrons when they reach the outer space charge is related to their average initial energy $\overline{W}_0$ by the equation

$$\overline{W} = \overline{W}_0 - \tfrac{1}{2}mu_0^2 \quad . \quad . \quad . \quad . \quad (32)$$

Substituting (31) in (32) now gives

$$\overline{W} = 1/(2h) \quad . \quad . \quad . \quad . \quad . \quad (33)$$

The mean kinetic energy of forward velocity of the electrons is therefore unchanged by passing through the potential minimum, remaining equal to kT. But, considering a metallic conductor as source of thermal noise, it is clear that treatment of an electron stream as a source of comparable thermal-agitation noise requires that the random velocities of the electrons shall be equally distributed both *forward and backward* along the direction of the current-flow. Again, referring to our definition of temperature, we are required to find a mean kinetic energy of random velocity, excluding any drift velocity common to all constituents of the system. We therefore regard the equivalent in volts of the *mean* of the emission velocities of the electrons as being added to the steady anode voltage, and the *deviations from the mean* as the source of thermal-agitation noise. If as an approximation we assume the mean electron velocity to be equal to the mean-square velocity, this means that we simply halve the value of u in all the energy calculations, and divide by four the kinetic energies which depend upon u^2.

The new mean value of kinetic energy of random velocity along the chosen direction is then $kT/4$. But in a perfect gas the mean energy of a particle along any one of a set of three Cartesian axes is equal to the equipartition value $kT/2$; the electrons with mean random energy $kT/4$ have therefore an effective temperature $T/2$, one-half the cathode temperature.

Actually the mean velocity in a Maxwellian distribution is $\sqrt{[8/(3\pi)]}$ times the root-mean-square velocity, so the mean velocity assumed in our approximation is in error by the difference between unity and $0{\cdot}921$, i.e. by $7{\cdot}9$ %. It might at first be thought that this would cause an er or of nearly 16 % in the calculated temperature, since this depends upon the square of velocity; but actually it is a question of deducting velocity from one group of electrons and adding to another, so that the error depends upon a difference of squares only, and is small, provided the two squares are nearly equal, which is true in this case.

We have thus shown that in a valve having a resistance which is finite and a function of space charge (i.e. a space-charge-limited valve) the total fluctuation noise is equal to the thermal-agitation noise in a corresponding resistance at a temperature of approximately half the cathode temperature, subject to the following corrections:—

(1) In practical valves, end-effects cause a fraction of the current to be temperature-limited, and therefore probably more "noisy." It might be worth while to try experiments with guard rings, so as to use only the central part of the cathode where the current can be fully space-charge-limited.

(2) The relation between slope resistance and effective resistance for thermal noise must be taken into account. [See, for example, equations (13), (18), (21), which indicate that the effective resistance is normally greater than the slope resistance.]

(3) Although the simple theory of thermionic emission has been well tested for pure metals, there is a slight possibility (though no actual evidence) that with complex emitting surfaces the space-charge adjacent to the cathode might have a temperature different from that of the cathode, though probably retaining a Maxwellian distribution of velocities. This can only occur if quantum effects prevent the free exchange of energy between the space-charge and the interior of the cathode.

(8) MECHANISM OF THERMAL-AGITATION NOISE IN SOLID CONDUCTORS

We have found that the fluctuation noise in a space-charge-limited valve may be represented as a thermal-agitation noise. Conversely, thermal-agitation noise in a metallic conductor may be represented as "shot noise" within the crystal lattice of the material, and without space-charge limitation.

Let us consider a conductor of length Δl and sectional area A, having n_0 free electrons per unit volume, and subjected to a uniform longitudinal electric field of strength E. Within a solid conductor, collisions between electrons and molecules are extremely frequent, and the drift velocity acquired under an applied electric field is small compared with thermal-agitation velocity; we may therefore assume a fixed time of flight τ between collisions, depending solely upon the distance between molecules and the temperature. Denoting the electronic charge and mass by e and m respectively, the mean drift velocity $\bar{u}$ is given by

$$\bar{u} = eE\tau/(2m) \quad . \quad . \quad . \quad . \quad . \quad (34)$$

From the definition of electric current as $i = dQ/dt$, it follows that if there is a small finite variation of charge ΔQ in a time Δt, the average current flowing is $\bar{i} = \Delta Q/\Delta t$. If, further, the charge is transferred from one end to the other of a length Δx (i.e. the current flows through a circuit of length Δx) during the time Δt, we may write

$$\bar{i}\Delta x = \frac{\Delta Q}{\Delta t}\Delta x = \frac{\Delta x}{\Delta t}\Delta Q = \bar{u}\Delta Q \quad . \quad . \quad (35)$$

since the ratio $\Delta x/\Delta t$ is the mean velocity. Now in the metallic conductor, ΔQ is equal to the product of the charge on an electron and the total number of electrons taking part, Δx may be replaced by Δl (provided the latter is taken small enough), and $\bar{u}$ is given by equation (34), so that

$$\bar{\imath}\Delta l = (A\Delta l n_0 e)\left[eE\tau/(2m)\right] \quad . \quad . \quad . \quad (36)$$

But the potential difference V between the ends of the conductor is the product $E\Delta l$ of field-strength and length, and the resistance R is the ratio of potential difference to current. Thus

$$R = \frac{V}{\bar{\imath}} = \frac{E\Delta l}{(An_0 e)\left[eE\tau/(2m)\right]} = \frac{2m\Delta l}{An_0 e^2\tau} \quad . \quad (37)$$

Comparing the solid-conductor problem with the shot-noise problem in a thermionic valve, we may say that equation (37) has related the mean current to the atomic mechanism, but it remains to determine the fluctuation noise due to the discrete nature of the mechanism. Provided that a current pulse is sufficiently short in duration compared with the period of frequencies capable of being observed, it is possible to evaluate the observable components of the Fourier analysis of the pulse without knowing its shape. For example, in dealing with shot noise in a temperature-limited diode, Moullin and Ellis (*loc. cit.*) showed that, knowing only the integral characteristic of the pulse due to a single electron, $\int i dt = e$, the components of radio frequency can be calculated. In our present problem of the solid conductor the unit pulse is not a current, but is of the form $i\Delta l$, which will be termed a "current-element." Combining expressions (34) and (35) for a single electron, and integrating over its time of flight, we have

$$\int_0^\tau (i\Delta l)dt = e\bar{u}\tau \quad . \quad . \quad . \quad . \quad (38)$$

If, therefore, we replace e in the analysis of Moullin and Ellis by $e\bar{u}\tau$, the components of the Fourier analysis will represent components of $i\Delta l$ in place of i. The time of flight of an electron within a conductor is even shorter than the transit time through a valve, so that the assumption that the pulse is so short that its shape has negligible effect on the radio-frequency components is a fortiori applicable in this case. If $2\pi/p$ is the period of the Fourier series, assumed to be long compared with the duration of the pulse but short compared with radio frequencies, the pulse $e\bar{u}\tau$ is found to be equivalent to a series of current-elements

$$\Sigma i\Delta l = (e\bar{u}\tau p/\pi)(\tfrac{1}{2} + \Sigma \cos npt)$$

In the present problem, unlike the shot effect, $\bar{u}$ may be either positive or negative, so that the constant term (steady current) will vanish on summing over a large number of pulses; the noise current-elements are left as

$$\Sigma i\Delta l = (e|\bar{u}|\tau p/\pi)(\Sigma \pm \cos npt) \quad . \quad . \quad (39)$$

Since the time $2\pi/p$ was taken to be very long, the order of harmonic n is high, and we may replace the summation by an integral. The resultant of the noise current-elements in a group of frequencies between n_1 and $(n_1 + dn)$ is then given by the equation

$$(i\Delta l)_{dn} = (e|\bar{u}|\tau p/\pi)\int_{n=n_1}^{n=n_1+dn} \pm \cos npt \,.\, dn$$

Expressing this in terms of frequency, we have $np = 2\pi f$, $dn = (2\pi/p)df$,

$$\therefore \quad (i\Delta l)_{df} = 2e|\bar{u}|\tau\int_{f=f_1}^{f=f_1+df} \pm \cos 2\pi ft \,.\, df \quad . \quad . \quad (40)$$

$$(i\Delta l)^2_{df} = 4e^2\bar{u}^2\tau^2\int_{f=f_1}^{f=f_1+df} \cos^2 2\pi ft \,.\, df$$

$$= 2e^2u^2\tau^2\int_{f=f_1}^{f=f_1+df} (1 + \cos 4\pi ft)df$$

But on averaging over a considerable period we have $\int \cos 4\pi ft \,.\, df = 0.$

The mean-square value of the noise current-elements from a single pulse is therefore

$$(\bar{\imath}\Delta l)^2_{df} = 2e^2\bar{u}^2\tau^2 \,.\, df \quad . \quad . \quad . \quad (41)$$

But if there are N electrons taking part, and each electron collides $1/\tau$ times per second, i.e. makes $1/\tau$ separate journeys per second. there are altogether N/τ randomly-phased pulses per second. Since they are in random phase we may add the squares of the random current-elements (this is assuming that the resultant of N random-phased vectors is $N^{\frac{1}{2}}$ times the unit vector), so that the resultant of the noise current-elements in frequency band df has a mean-square value

$$(\bar{I}\Delta l)^2_{df} = 2Ne^2u^2\tau \,.\, df$$

and $$\bar{I}^2 = (2Ne^2u^2\tau \,.\, df)/(\Delta l)^2 \quad . \quad . \quad . \quad (42)$$

But if current $\bar{I}$ flows through resistance R the corresponding potential difference is, by definition of R, equal to $\bar{I}R$; the mean-square noise voltage corresponding to (42) is therefore

$$\overline{V}^2_{df} = R^2\bar{I}^2_{df} = (2R^2Ne^2u^2\tau \,.\, df)/(\Delta l)^2 \quad . \quad . \quad (43)$$

Using equation (37) to eliminate N, e, and τ,

$$\overline{V}^2_{df} = 2R \,.\, 2m\bar{u}^2 \,.\, df \quad . \quad . \quad . \quad . \quad (44)$$

It is clear that the only velocity which will contribute to the current between two points is the velocity along the direction of flow; in other words, $\bar{u}^2$ is to be taken as the mean-square of the component of thermal-agitation velocity in one specified direction. But the equipartition value of the thermal energy contributed by velocity components in one given direction is $\frac{1}{2}m\bar{u}^2 = \frac{1}{2}kT$ for each particle. Equation (44) therefore becomes

$$\overline{V}^2_{df} = 4RkT \,.\, df \quad . \quad . \quad . \quad . \quad (45)$$

which is the well-known expression deduced thermodynamically by Nyquist.

Whereas in Nyquist's derivation the internal mechanism was not involved, owing to the use of overall

energy-exchanges, in the treatment given above the mechanism is exposed, but all factors peculiar to the material, namely the number of electrons taking part in conduction, time of flight, and mass and charge of the electron, have been eliminated in terms of the resistance and the function kT. Equally with the thermodynamic proof, therefore, the derivation presented above indicates that the thermal-agitation noise is a function only of ohmic resistance and temperature, and not of the structure of the conductor involved. The thermionic valve is therefore included, so long as it has a determinable ohmic resistance and temperature.

It is interesting to note that in Nyquist's derivation there was no upper limit to the frequency to which the expression for noise energy was applicable; something in the nature of quantum restrictions was necessary to prevent the total energy from becoming infinite if the frequency range was extended to infinity instead of being confined to the radio band. In the derivation used above it is obvious that the expression ceases to be valid when the frequency has a period comparable with the time of flight of the electron within the conductor, for the Fourier analysis must then be modified and will depend upon the shape of the pulse. There is therefore seen to be a limit to the validity of the expression, though the limiting frequency will be somewhere in the region of heat radiation.

(9) APPLICATION TO THE THERMIONIC VALVE

The remaining difficulty is the transition from a temperature-limited to a space-charge-limited regime in a thermionic valve: we have yet to decide what constitutes the essential distinction between the two states. It would seem that the presence of a potential minimum, however small the barrier which it imposes, is one criterion; for, provided there is such a barrier, some electrons emitted will return to the cathode, and the space-charge adjacent to the cathode will be in thermal equilibrium with it. The initial temperature of the space-charge will then be fixed at the cathode temperature, and, as we found above, the effective temperature of the outer space-charge is about half that of the inner space-charge. The transition in any real valve will be gradual, owing to lack of uniformity both of the anode-to-cathode field along the length of the cathode and of the cathode temperature.

Another criterion of the state in which the thermal-agitation treatment is applicable is that the field from the anode should terminate on space-charge, not on an actual metallic electrode. For if the field from the anode ends on a metallic electrode, the emergence of any electron from that electrode constitutes a disturbance; but if the field terminates on electrons, constituting space-charge, which are moving towards the anode with approximately uniform velocity, the presence of electrons travelling at the exact mean velocity at every point does not create a disturbance; it is only the deviations from the mean which are effective.

In a diode, but not in more complex valves, the two criteria are identical. As an example of the more complex valves, consider a screen-grid tetrode. In this the screen-anode space corresponds nearly to a temperature-limited diode with the screen as virtual cathode. Most of the anode field terminates on the screen wires, so that the injection of electrons into this space through the screen may be expected to produce a shot noise at the anode, of the magnitude predicted by equation (1). The same effect is to be expected to a less extent in triodes, depending upon the closeness of the grid winding; this may explain the experimental results of F. C. Williams with an L.S.5 triode.*

(10) TWO RESISTANCES IN PARALLEL

Another point which is of importance for the comparison of any theory of thermal noise with experimental results is the magnitude of the resultant fluctuation voltage from two resistances at different temperatures connected in parallel. Transferring equation (45) from voltage back to fluctuation current, which we saw was the fundamental phenomenon, we find that

$$\bar{I}^2_{df} = (4kT/R) \cdot df$$

where $\bar{I}^2$ is the mean-square fluctuation current. But $\bar{I}^2$ is made up of a very large number of random vectors, so that to combine two such currents, arising in resistances R_1 and R_2, we merely add their squares. Thus

$$\bar{I}^2_0 = \bar{I}^2_1 + \bar{I}^2_2 = (4kT_1/R_1 + 4kT_2/R_2) \cdot df \quad . \quad (46)$$

Equation (46) for the total fluctuation current flowing when two resistances R_1 and R_2 at temperatures T_1 and T_2 are connected in parallel reduces to

$$\bar{I}^2_0 = 4k \cdot \frac{R_2T_1 + R_1T_2}{R_1R_2} \cdot df \quad . \quad . \quad . \quad (47)$$

But the resultant resistance of the two in parallel is $R_0 = R_1R_2/(R_1 + R_2)$. The noise voltage corresponding to the current given in equation (47) is therefore

$$\bar{V}^2_0 = R^2_0\bar{I}^2_0 = 4k \cdot \frac{R_1R_2(R_2T_1 + R_1T_2)}{(R_1 + R_2)^2} \cdot df \quad . \quad (48)$$

This equation has been previously derived by Llewellyn.†

(11) ACKNOWLEDGMENTS

Any scientific worker is indebted to his predecessors, but the present author, owing to his own lack of experimental work on the problem, is particularly indebted to the writers of previous publications, even though he has disagreed with them. In particular, his thanks are due to Mr. E. B. Moullin, who first interested him in this subject and with whom he has had a number of valuable discussions.

The author is also indebted to Marconi's Wireless Telegraph Co., Ltd., for the preparation of lantern slides used in the presentation of this paper.

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DISCUSSION BEFORE THE WIRELESS SECTION, 5TH JANUARY, 1938

Mr. E. B. Moullin: In his discussion of Fig. 1 the author points out that the deviations from the mean increase with the current, even though the flow of electrons becomes relatively smoother. It is a basic theorem of statistics that, in circumstances such as those depicted in Fig. 1, the mean-square departure from the mean increases in direct proportion to the mean value. It is both well known and remarkable that this theorem, true in the limit of very large numbers, is substantially true when the number of events is quite small. This can be illustrated well by means of the diagrams in Fig. 1. Thus we find that the mean-square departures from the mean in Cases A and D of Fig. 1 are 1·3 and 0·6 respectively, if the baseline is taken as 20 units of time. There is no reason why we should take A, B, C, or D, in preference; and therefore the natural course is to take these possible chances of succession one after the other, and then the long-time mean of the mean-square fluctuation is 0·92. According to the statistical theorem I have mentioned, if we have 5 times the current the mean-square departure should be 5 times this amount, i.e. 4·6. We have a particular case of this in the sum curve of Fig. 1; and the mean-square departure is 6·3. Thus we should expect the value 4·6, whereas we get 6·3; but this is too rough an approach to be a fair test. There are 10 possible summation curves of Cases A to E taken in pairs, 10 more possible combinations taken three at a time, and 5 combinations taken four at a time. I have made the 10 possible additions two at a time, and find the mean-square deviation of these comes to 2·27. For the 5 possible combinations four at a time I find the mean-square deviation is 4·53. As an example, let us suppose that the mean-square deviation is proportional to the mean, and equal to 4·53 when the mean is 4. Then, when the mean current is 1, 2, 4, or 5 electrons (I have not worked out the figures for 3), the deviations should be 1·14, 2·27, 4·53, and 5·67 respectively. The measured deviations for the sample curves given in Fig. 1 are in fact found to be 0·92, 2·27, 4·53, and 6·3. The agreement between these sets of values is fairly good, and the example serves to illustrate this important theorem.

I feel that Nyquist's theorem still requires to be stated more rigidly. In its present form it is certainly correct for all linear networks which do not include thermionic valves, but when such are included we still do not know how to apply it to give the correct result, though I consider the author's method of obtaining the effective value of the internal resistance (page 525) is a notable step forward to this end.

Section (5) begins by stating the author's belief that shot and thermal effects are different aspects of the same general principle. I have always thought, and I think often stated, that until we had a general theorem which would include shot and thermal effects as special cases of one general principle, this very intricate noise problem would remain in an unsatisfactory state. In my opinion Section (8) of this paper is a real step towards this general treatment, and is perhaps the most illuminating theoretical contribution to the whole subject which has been made in the last decade. I have often tried to obtain the thermal-agitation formula from the shot-effect principle, and have always failed dismally.

Lately I was talking to Prof. Schottky in Berlin, and he told me he had derived a formula for the thermal-agitation principle from a shot-voltage mechanism. The proof has not yet been published, and I shall be interested to see whether it is the same as the present author's derivation.

From one point of view it has always been difficult to understand why the passage of a steady current through a resistance did not increase the fluctuation voltage produced by it. For if most methods of calculating the shot voltage produced by a temperature-limited thermionic current (for example, that which Mr. Ellis and I produced some years ago),* are examined critically, it is difficult to find any step in the argument which could not be applied to effects inside a conductor. I think the paradox has been resolved by the analysis of Section (8) of this paper: for this brings out clearly that the number of random events in the conductor are governed by the number of free electrons in it, and not by the average current passing through it. Such a current will not produce a first-order effect on the number of random events, and will possibly produce no effect at all.

In spite of all the work that has been done, however, the background noise in an amplifier valve still cannot be calculated. In the last 6 months Prof. Schottky has produced several long papers on the shot effect in space-charge-limited conditions. I have so far been unable to disentangle fully his basic idea from the analysis in which it is clothed. Schottky's formula is appreciably better than the old classic expression of Llewellyn, but it is still in bad agreement with facts.

On page 529 the author observes: "In practical valves, end effects cause a fraction of the current to be temperature-limited, and therefore probably more 'noisy.' It might be worth while to try experiments with guard rings, so as to use only the central part of the cathode where the current can be fully space-charge-limited." That work has just been completed in Germany,† but the results do not appear to approach the theoretical value of Schottky more closely than they would have done if no precautions had been taken.

Dr. F. C. Williams: The author deals with this subject from the point of view of the physicist, whereas I have examined it experimentally.

* *Journal I.E.E.*, 1934, vol. 74, p. 323.
† H. JACOBY and L. KIRCHGESSNER: *Wissenschaftliche Veroffentlichungen aus den Siemens-Werken*, 1937, vol. 16, p. 42.

I do not feel competent to question the validity of the author's application of a thermodynamic principle to the problem of thermionic balance, but I see several difficulties in applications of this sort which have been made in the past. Thus Llewellyn considered a box containing a thermionic valve and a resistance uniformly heated to a temperature τ sufficient to enable a copious emission of electrons to take place. On that hypothetical experiment he based his result that the noise in the valve must be a thermal noise and must be given by $\overline{V}^2 = 4\rho k\tau df$. Experiment persists in showing, however, that the relevant value of τ would not be the temperature of the box but half this value. Thus there is either some flaw in Llewellyn's original analysis or some factor which militates against the truth of such applications. Further, it may be noted that in this uniform-temperature box we apparently have a steady transfer of energy from the resistance to the valve, which is a contradiction of the thermodynamic law. If, now, a grid is introduced into the valve and a resistance connected between the grid and cathode, the fluctuations generated in the valve are vastly augmented, and there would probably be a transfer of energy from the valve to the resistance. My own experiments show that even if the resistance is not present but the grid is simply short-circuited to the cathode, the apparent temperature of the anode stream may be from 10τ to 40τ. Until these difficulties have been satisfactorily resolved, some doubt must attach to a thermal representation of valve fluctuations based on thermodynamic considerations.

Thus if valve noise be interpreted in terms of thermal agitation, it is often necessary to assume an effective temperature very much higher than the melting point of the cathode material; further, the temperature is a function of the electrode structure and of the operating conditions. Such interpretation appears rather artificial, and has little to offer which counterbalances the enormous technological advantages of the shot interpretation.

Mr. Moullin mentioned the work of Schottky in attempting a shot explanation of the fluctuations in space-charge-limited valves. Schottky has produced a curve calculated on that basis which Mr. Moullin says is little better than earlier attempts as regards its agreement with experiment. The curve is, however, not vastly out of agreement with some experimental results—the discrepancy being of the order of $1\cdot 5$ to 2. On the other hand, the only experimental verification of the thermal expression has been made either in the retarding-field region or very close to it, where the $\tau/2$ discrepancy from Llewellyn's original formula is found. It is interesting to note that this discrepancy can readily be explained in terms of pure shot theory.

In conclusion, I may perhaps mention that the process used by the author in Section (10) to derive the fluctuation generated across two resistances in parallel was employed in one of my own papers* to deduce the fluctuation voltage generated by a space-charge-limited current traversing a resistance. It was noted then that the method could be applied to the analogous problem of two resistances in parallel.

Mr. O. E. Keall: The published results of shot-noise investigations carried out in this country and also in Japan and Germany 2–3 years ago show a considerable discrepancy both in the temperature-limited region and also in the space-charge region, although the valves concerned had similar anode-current/heater-current characteristics. It would therefore seem that an experimental investigation of this subject on a much larger scale than has hitherto been conducted is desirable. Particularly is this the case because hitherto the investigations have been limited to consideration of one or two of the variables in the valve only (either resistance or current). In spite of the elegance of the author's analysis, I do not see how one can apply the formula he gives in the case of the valve with infinite resistance or even in the case of the valve with negative resistance, because experimental results indicate that there is no great difference between these cases and that of the valve with normal characteristic.

Mr. W. H. Aldous: A theory of fluctuation noise should agree with practice over at least part of the range of the valve characteristic, and I do not think it can be said to be a complete theory until it agrees with practice over the retarding-field region, the normal working region, and the temperature-limited region. I do not know in which of these regions the author's theory agrees with experiment.

Dealing with Section (4), I do not see that Nyquist proves the universality of thermal-agitation noise by his treatment. He merely says that some source passes energy into a resistance outside itself. Now the second law of thermodynamics does not say what that emerging energy should be, and why one should assume it is thermal-agitation noise. The author proposes to use a value of resistance in the thermal-agitation formula different from the valve slope resistance, which he derives from consideration of the power absorbed, given by $P = V^2/R'$. For a characteristic of the form $i = aV^n$ this gives

$$R' = \frac{2n}{n+1}R_a$$

If he had started instead with

$$P = I^2R''$$

(which is actually the form used by Nyquist), and therefore

$$R'' = \frac{1}{2I}\frac{dP}{dI}$$

a different value of effective resistance would have been obtained, namely

$$R'' = \frac{n+1}{2}R_a$$

I think the idea that the power is produced in the valve itself is incorrect. It arises from the random transit of the electrons across the electrode space producing a fluctuating voltage across the load. Since the valve is in parallel with the load, a certain proportion of the power will be dissipated in the valve slope resistance, which therefore requires no modification. This is in accord with the experimental work of both Schottky and F. C. Williams, who have shown that, in the retarding-field region represented by equation (19), the shot noise is

* *Journal I.E.E.*, 1936, vol. 79, pp. 352 and 354.

given accurately by equations (4) and (5). This can be seen to be true on general grounds, since in the retarding-field region there is no question of space-charge control, all electrons with initial energy greater than some minimum reaching the anode. These electrons will arrive randomly in time, and it is this randomness in time—not randomness in velocity—which gives rise to the shot voltage across the load.

At the end of Section (7) the author tries to show that a deviation of velocity from the mean can cause noise; but I think he takes an unfortunate example. A few of the electrons are stopped by positive ions, and this means that the steady rate of arrival of the electrons at the anode is altered, a condition which must give rise to shot noise. With regard to the author's method of deriving the value $\tau/2$, since in the case he considers there are so many more electrons with low forward velocities than with high forward velocities, the deviations about the mean will not be randomly distributed. Therefore I feel very doubtful as to whether the mean value of kinetic energy of random distribution along the chosen direction can be taken to be $k\tau/4$.

Finally, I should like to put forward a plea for the use of conductances rather than resistances in these fluctuation formulae, in view of the consequent simplification of the mathematics. Thus equation (48), if extended to several conductances $S_1, S_2, \ldots S_n$ in parallel at temperatures $\tau_1, \tau_2, \ldots \tau_n$ respectively, becomes simply

$$\overline{V}_0^2 = 4k\frac{\sum_1^n S_n\tau_n}{\left[\sum_1^n S_n\right]^2}df$$

where each conductance is now associated with its own temperature.

Dr. W. F. Rawlinson: I should like to ask the author a question in relation to the assumed or calculated temperature of the electron stream. Although the valve has been evacuated it must still contain a large number of molecules or atoms. Since the author derives for the electron-stream temperature a value which is about half the cathode temperature and which bears no relation to the anode temperature, and since his derivation depends on the equipartition theory, are we to assume that the residual gas between the anode and cathode is also at half the temperature of the cathode?

Considering a cathode which gives perfectly uniform emission and therefore no shot noise, and, according to the author, no thermal-agitation noise, will the electron stream be at absolute zero temperature; and, if so, what is the temperature of the residual gas?

Mr. H. D. McD. Ellis: The paper is a valuable contribution towards the solution of these fluctuation problems; seeing the elegance of the author's treatment I regret that I was not trained as a physicist also. I am particularly struck by the way in which the author has cleared up some of the troubles with which Mr. Moullin and I were concerned when we were preparing our paper* about 5 years ago. For example, I am interested in his methods of obtaining the thermal-agitation voltages in two resistances at different temperatures, and of determining the effective anode impedance of a thermionic valve from power considerations. We obtained the correct solution to the first of these problems 5 years ago, but not, I fear, in so neat a fashion.

* *Journal I.E.E.*, 1934, vol. 74, p. 323.

Mr. W. S. Percival (*communicated*): On page 525 the author introduces a correction to the slope resistance of a diode valve to take account of the curved characteristic for purposes of noise calculation. I am unable to follow the author's argument, but equation (21)* leads to a result opposed to well-known theory. If in this equation we make V negative and large compared with $1/b$, i.e. if we work in the retardation region with a small current, so that we can neglect the space charge, then approximately, $R' = 2R_a$. It has, however, been shown by F. C. Williams† that this is the one condition in which the diode must behave as an apparent (slope) resistance at half the cathode temperature without any correction being necessary.

A more satisfactory line of argument is to consider a choke placed in the anode circuit of the diode, the anode of which is connected via a condenser to a transmission line terminated by a resistance equal to the slope resistance R_a of the diode. Under these conditions the noise power transferred from the resistance to the diode and hence from the diode to the resistance, depends simply on the slope resistance of the diode and is independent of the curvature of the characteristic. If the diode could be at the same temperature throughout and there were no external source of energy, then Nyquist's original argument‡ would hold. In fact, however, the cathode of the diode is at one temperature, its anode is at another, and external energy is available from a battery. The original proof of Nyquist does not, therefore, apply.

On page 528 the author states " There is therefore no thermal exchange between the cathode and the electrons between potential minimum and anode." This cannot be true, however, since the electrons between the potential minimum and the anode form part of the space charge. Let us suppose that there is a certain rush of electrons past the space-charge minimum, then that portion of the space charge will be increased. The increased negative field will prevent some electrons which would otherwise pass the minimum from doing so. Some of these electrons will fall back into the cathode. Hence those electrons which have passed the potential minimum can still, indirectly, influence the cathode. It is true, as the author says, that no electrons which have passed this point can return. Their electric field is still effective, however, and can influence those electrons which are closer to the cathode.

Prof. W. Schottky (Germany) (*communicated*): Contrary to the " relative temperature theory," in which the electron stream is compared to a gas having a uniform velocity superimposed on the Maxwellian motions of the molecules, I consider that there is no moving co-ordinate system with respect to which the velocity distribution of the electrons has an effectively Maxwellian character: the indefinitely large velocities in a backward direction are missing.

* The a in this formula appears to be a misprint [corrected for the *Journal*].
† *Journal I.E.E.*, 1936, vol. 78, p. 326.
‡ *Physical Review*, 1928, vol. 32, p. 110.

Our work shows that the rigorous treatment of the space-charge problem appears rather as a shot effect which approaches the $\tau/2$ law when the current is sufficiently reduced by space charge. I have explained how in a retarding field (without space charge) it is possible to find the "thermal complement" of the cathode-to-anode electron stream, which would make the whole system equivalent to a thermal one. I have not, however, succeeded in finding the "thermal complement" for a space-charge current.

An objection to the "relative temperature theory" is that the rigorous theory, under ideal conditions, yields the value $1 \cdot 272\tau/2$ for the apparent temperature.* This departure from the $\tau/2$ law is large compared with that which can arise from the insufficient consideration of mean drift velocity suggested towards the end of Section (7) of the paper.

I have nothing to add to Section (8), which is more complete than my own work on this point, since it gives the constant, $4k$, correctly. But the following may be of interest. For the region of very high frequencies, I have calculated the frequency spectrum on the assumption that all electrons have equal velocities in the direction of the current under investigation, but that the lengths of free path are distributed in a random manner. This can be compared to the flicker effect, by considering that the mean impulse time of an electron in the conductor corresponds to the mean life of an extraneous molecule in the flicker effect. One then calculates the energy which on short-circuit is dissipated by this frequency spectrum in an ohmic resistance, and finds (except for a factor approximately equal to unity, of which I cannot yet be certain), the value $k\tau/t$ where t is the mean impulse time. This result is very satisfactory, for it shows that the thermal energy of a degree of freedom in an electronic conductor will on the average be absorbed and restored as often as corresponds to the mean impulse time of electrons, irrespective of the number of electrons on the conductor.

Mr. D. A. Bell (*in reply*): Both Mr. Moullin and Mr. Aldous have doubts as to Nyquist's theorem. Undoubtedly, care is necessary in applying it; it was for this reason that a substantial part of the paper was devoted to discussion of the values of "resistance" and "temperature" to be used. I would go so far as to say, however, that the difficulty is not, as Mr. Moullin suggests, that we do not know how to apply Nyquist's theorem to thermionic valves in general, but that (*a*) we cannot make a valve conforming to ideal laws, and (*b*) we have not yet seen how to modify the theory for valves which are only partially space-charge-limited.

Much confusion seems to arise from the idea of some absolute distinction between different types of fluctuation noise; thus Mr. Aldous states "Now the second law of thermodynamics does not say what that energy should be, and why one should assume it is thermal agitation noise." In my view there is one *assumption*, and one only, that is made in setting out Nyquist's theorem; and that is that it is possible to have two elements of an electric circuit which are connected by electrical conductors, but isolated from each other so as to prevent the direct exchange of other forms of energy. I do not think this is any more unreasonable than the ideas used throughout classical thermodynamics, such as the perfect gas, perfect heat insulator, or perfectly-reversible heat engine. Given this assumption, when a space-charge-limited valve and a resistance are connected together, there must be energy transferred from the valve which is proportional to the temperature of the valve's resistance, and surely such energy must be described as thermal-agitation energy, whatever the internal mechanism by which it is produced.

With regard to the experiments of Prof. Schottky and his colleagues, which Mr. Moullin mentions as having full precautions in the way of guard-rings, is not the best criterion of achievement of the "ideal" system the anode-current/anode-voltage law? In Prof. Schottky's diode one would expect a 3/2 power law, but the published curves seem to indicate a law nearer $1 \cdot 3$ than $1 \cdot 5$ for tube No. 6; tube No. 7 is sufficiently complex to have other difficulties.

If Dr. Williams is not prepared to discuss my analysis, it is doubtful whether there is much value in replying to his objections to Llewellyn's work. As will be seen from a study of Section (7) of the paper, I believe the resistance of the valve must be at a temperature different from that of the cathode, so the idea of a uniform-temperature enclosure including the whole of a valve is ruled out. The same section gives the basis for my belief that there is real significance in a modified $T/2$ law for a space-charge-limited valve. In the case of the triode amplifying valve, with a resistance connected between grid and filament, I see no reason to depart from the normal theory of the amplifying valve, in which the output a.c. power is derived from the source of steady anode potential, even if that source be only the mean initial velocity with which the electrons are emitted from the cathode. As explained at the end of Section (9) of the paper, I do not consider Dr. Williams's results with grid short-circuited to cathode to be incompatible with my theory. The shot interpretation is only applied to space-charge-limited valves by the addition of an arbitrary correction factor (or "smoothing factor") which Dr. Williams denotes by $\dot{A}$; until this factor has been given a rational basis it cannot be regarded as having any place in a scientific theory, or used (other than empirically) as an aid to the design of apparatus.

In his statement that in the retarding-field region the $T/2$ law can be readily explained in terms of pure shot theory, Dr. Williams is presumably referring to a paper in which he examined this question.* I regret that I cannot accept his treatment as exact, though it gives a useful approximation. For he assumes that $Ve >> kT$, and $x >> kT$, where V is the working anode voltage, ranging from about $-0 \cdot 5$ to zero, T the cathode temperature, and x the work function of the cathode. Using values given by Benjamin, Cosgrave, and Warren in a recent paper,† I have prepared the figures in Table A for various cathodes.

Thus for an oxide-coated cathode (which was the type used by Dr. Williams for the retarding-field experiment) x is about 10 times kT, but Ve is only about 6 times kT at the extreme limit of the range ($V = -0 \cdot 5$ volt); this

* *Wissenschaftliche Veroffentlichungen aus den Siemens-Werken*, 1937, vol. 14, p. 15.

* *Journal I.E.E.*, 1936, vol. 78, p. 326.
† *Ibid.*, 1937, vol. 80, p. 401.

does not seem to justify the approximations adopted for the whole range 0 to $-0 \cdot 5$ volt. I do not think the thermal theory has previously been set out in sufficient detail for application to practical valves [see Section (3) of the paper on previous versions of the thermal theory].

I should like to support Mr. Keall's suggestion for more comprehensive experimental work, particularly as I personally have no facilities for experiment and must rely upon the published results of others to verify my hypotheses.

All valves which have an infinite resistance are, in my opinion, operating under conditions which correspond to temperature-limitation, whatever may be the space-charge distribution at some point remote from the anode; the "pure shot noise" formulae are therefore applicable to such valves.

Mr. Aldous mentions three regions of the valve characteristic, but I think we must in practice make four divisions:—

(i) The temperature-limited region. I have not modified the "pure shot noise" formulae, which I believe are the complete solution of this case.

Table A

Cathode material	Operating temperature	Work-function	kT/e
	°K.	electron-volts	volts
W	2 500	4·52	0·214
W-Th	1 900	2·77	0·163
W-O-Cs	810	0·7	0·069
BaO, SrO, Cao	1 040 to 1 100	0·95	0·089 to 0·094

(ii) The region in which the current is partially but not completely space-charge-limited. This is the practical working condition in amplifying valves, and there is no theory which has been shown to be in agreement with experiment over this region. But the theory given in this paper can be extended to give some idea of the mixed case; this work is in hand and will be published in due course.

(iii) Completely space-charge-limited region. The values of noise calculated by my theory are in close agreement with those predicted by Prof. Schottky. So far as I am aware, this state has never been accurately realized experimentally; but the results of measurements made by Prof. Schottky's colleagues are in moderate agreement with the theoretical limiting value.

(iv) Retarding-field region. For the reasons given above, in reply to Dr. Williams, I do not regard the retarding field region as susceptible to such simple analysis as is sometimes suggested.

I agree that a different effective resistance would have been obtained by considering I^2R in place of E^2/R, but I believe the latter is correct. Any resistance must in practice be shunted by a capacitance, even if only its own self-capacitance; the fluctuation current then charges this capacitance to a corresponding potential, and the capacitance then discharges through all circuit elements which may be connected in parallel across it. The energies dissipated in each are therefore distributed according to factors of the type E^2/R. I have already dealt with the shot-noise interpretation of the retarding-field region, and the reason for describing the component of noise which is proportional to the resistance and temperature of the valve as thermal noise, whatever the mechanism. In saying that the slope resistance requires no modification, it would have been more helpful had Mr. Aldous mentioned which of equations (6) to (10) of the paper he considers to be in error.

In Section (7) of the paper, it will be seen that the mean energy $kT/4$ was found by integrating the energy over all electrons present and dividing by the total number present; it therefore implicitly takes into account the actual law of distribution of velocities, which is admittedly not Maxwellian.

I would willingly endorse the use of conductances rather than resistances, but when comparisons with previous work are involved this might cause difficulty to the reader.

The solution of Dr. Rawlinson's intriguing problem is to be found in the conditions necessary for equipartition to occur. The only application of equipartition in the paper is to the energies of the electrons in the immediate neighbourhood of the cathode, where the free path is likely to be of short duration since the density is very high. Beyond the potential barrier, which is the region where the temperature was stated to be $T/2$, no such equipartition is assumed, and in fact it is improbable that there are sufficient collisions between electrons and molecules, compared with the rate of energy exchange due to collisions between gas molecules and the envelope of the valve, to establish equipartition between the residual gas and the electron stream. In the extreme case of uniform emission, the electron stream would be initially at zero temperature, but would be heated by the residual gas in so far as there were collisions to give a tendency towards equipartition.

I am indebted to Mr. Percival for pointing out the error in equation (21) in the proof copies of the paper; this has now been corrected. In the retarding field region, if $1/b = V$, then $R' = R$ (for evidence that this is not remote from the practical case, see my reply to Dr. Williams on this subject). The argument that electrons near the anode can influence subsequent emission does not destroy the fact that they are not themselves in thermal equilibrium with those near the cathode.

In reply to Prof. Schottky, I have not found it necessary to assume a Maxwellian distribution of velocities in the outer space-charge (see my reply to Mr. Aldous). According to equation (13) of the paper, my theory may be said to give an equivalent temperature of $1 \cdot 2T/2$ (not $T/2$) for a valve of 3/2 power law, since my expression is $V^2 = 4(1 \cdot 2R)kT/2$, against Prof. Schottky's $1 \cdot 272T/2$; I think the residual difference of 6 % could be due to the approximation made at the end of Section (7).

The scope of the paper is to derive the fluctuation noise to be expected from a metallic resistance and from thermionic valves obeying certain ideal laws. The latter cannot in practice be constructed and measured, but this theory of the simpler cases prepares the ground for a treatment of the more complex conditions corresponding to practical valves, which should be both of material value and capable of experimental verification.

THE ALTERNATING-CURRENT RESISTANCE OF HOLLOW, SQUARE CONDUCTORS*

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(*Paper first received* 29*th September, and in final form* 2*nd December*, 1937.)

SUMMARY

An approximate formula for the alternating-current resistance of isolated, hollow, square conductors, including the solid conductor as a special case, is developed theoretically. Experimental results are given to show that this formula is correct to within about 2 % at all frequencies.

Formulae for the proximity effects in single-phase and 3-phase systems are also developed. These formulae are based partly on theoretical development and partly on experimental results. The experimental results cover most of the values likely to be encountered in practice.

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LIST OF SYMBOLS

All conductors are assumed to be straight, of uniform section, and parallel to each other.

I = total current in conductor.

R = direct-current resistance of conductor per cm. length, in c.g.s. units.

R' = alternating-current resistance of conductor per cm. length, in c.g.s. units. [Alternating-current or effective resistance is defined to be the quotient of the power loss in the conductor by the square of the effective (r.m.s.) value of the alternating current.]

R_0 = alternating-current resistance of an isolated conductor per cm. length, in c.g.s. units.

F and F' = complete elliptic integrals of the first kind to moduli κ and $\kappa_1 [\kappa_1 = \sqrt{(1-\kappa^2)}]$

E and E' = complete elliptic integrals of the second kind to moduli κ and κ_1.

f = frequency in cycles per sec.

$\omega = 2\pi f$.

(p, q) = co-ordinates of a point P in section of conductor relative to the centre of the section as origin.

LIST OF SYMBOLS—*continued*

(x, y) = co-ordinates of a point X in section of conductor relative to the point P as origin.

$\iint^P F(x, y)\, dx\, dy$ = integral of the function $F(x, y)$ taken over the whole area of the section of the conductor.

$\iint^S F(p, q)\, dp\, dq$ = integral of the function $F(p, q)$ taken over the whole area of the section of the conductor.

E_p = e.m.f. induced at point P per cm. length of conductor by a current I distributed uniformly over the conductor section.

E'_p = e.m.f. induced at point P per cm. length of conductor by the eddy currents in the conductor.

E_x = e.m.f. induced at point X per cm. length of conductor by a current I distributed uniformly over the conductor section.

$\sigma_p = E_p/(\omega I)$.

$\sigma_x = E_x/(\omega I)$.

$\mu_p = E'_p R/(\omega^2 I)$.

L = self-inductance of conductor at zero frequency.

$$l = \iint^S \mu_p\, dp\, dq.$$

i_p = eddy-current density at P.

d = side of square section. (In developing formulae for the alternating-current resistance, the side of the section is taken as unity. This simplifies the mathematics and does not affect the validity of the final result in which the section dimensions do not appear.)

ρ = resistivity of conductor material in c.g.s. units.

s = spacing between axes of conductors in a single-phase system. (In a 3-phase system, s = spacing between axes of adjacent conductors.)

t = thickness of wall of conductor.

$\alpha = d/s$.

$\beta = 2t/d$. (For a solid conductor $\beta = 1$).

$$c_1 = \frac{1}{\beta(2-\beta)}\iint^S (\sigma_p - L)^2\, dp\, dq.$$

$$c_2 = \frac{1}{\beta(2-\beta)}\iint^S (\mu_p - l)^2\, dp\, dq.$$

(1) INTRODUCTION

Formulae are developed in this paper for the effective resistance to alternating currents of hollow conductors

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

of square section. Such conductors will be referred to as "square conductors." The eddy-current losses in square conductors are in most cases higher than in conductors of other sections, but this shape of conductor has other advantages which in many cases outweigh this disadvantage. Some of these advantages are:—

(a) The square section has a better space factor than the round section for such purposes as armature or field-coil windings.

(b) For large conductors, such as busbars, a hollow, square conductor can be built up out of conductors of rectangular, channel, or angle sections. Built-up conductors of this type may be less costly than hollow conductors of circular or other cross-sections.

(c) In built-up conductors, gaps may be left between the parts so that the inner surface of the conductor is ventilated. The increase of current-carrying capacity on account of improved heat dissipation often more than offsets the loss of current-carrying capacity, on account of greater eddy-current losses as compared with a conductor of circular cross-section.

The mathematical determination of the eddy-current losses in square conductors involves difficulties even more serious than those encountered in the determination of the losses in circular conductors, and a rigid solution cannot be obtained at present. J. D. Cockcroft* has shown how the eddy-current losses in an isolated, rectangular conductor may be determined precisely at very high frequencies. He has further shown that mathematical corners to the rectangle are not of great importance, since the effect of rounding the corners with a radius of curvature equal to 1/40th of the perimeter of the section is only to decrease the resistance by about 5 %. Most rectangular conductors manufactured to-day have radii of curvature at the corners appreciably less than this. The validity of Cockcroft's formula has been verified experimentally at high frequencies by W. Jackson.† In the present paper a low-frequency formula for the isolated, square conductor is developed, and it is shown how a simple modification enables the range of this low-frequency formula to be extended until it reaches the high-frequency range in which Cockcroft's formula may be used. Experimental results are given to confirm the accuracy of the formula developed.

Although the conductors of a system are often spaced so far apart that they may be treated as isolated conductors, this is not always the case. The theory involved in developing formulae for single-phase and 3-phase systems is exceedingly complicated, and the author has made use of his experimental results in order to develop semi-empirical formulae for these cases. These formulae are in agreement with low- and high-frequency formulae developed on strict theoretical grounds at the two ends of the frequency-range, and agree closely with experimental results in the intermediate frequency-range.

(2) THE ISOLATED CONDUCTOR

Cockcroft‡ has shown that the ratio of the alternating-current resistance to the direct-current resistance of isolated, solid conductors of rectangular cross-section at high frequencies is given by equation (1).

$$\frac{R_0}{R} = \frac{2}{\pi^{3/2}}(E - \kappa_1^2 F)^{\frac{1}{2}}(E' - \kappa^2 F)^{\frac{1}{2}}(F + F')\left(\frac{2\omega}{R}\right)^{\frac{1}{2}} \quad . \quad (1)$$

The ratio of the two sides of the rectangle defines the values of E, F, etc., by equation (2).

$$\text{Ratio of sides of rectangle} = \frac{E - \kappa_1^2 F}{E' - \kappa^2 F'} \quad . \quad (2)$$

For the square conductor, the ratio of the sides is unity, and therefore

$$\kappa = \kappa_1 = 1/\sqrt{2}; \quad E = E'; \quad F = F'$$

$$\frac{R_0}{R} = \frac{4F}{\pi^{3/2}}(E - \tfrac{1}{2}F)\left(\frac{2\omega}{R}\right)^{\frac{1}{2}}$$

$$= \sqrt{\left(\frac{2\omega}{\pi R}\right)} = 2\sqrt{\left(\frac{f}{R}\right)} \quad . \quad . \quad . \quad (3)$$

Equation (1) was developed on the assumption that the effective depth of penetration of the current at high frequencies is equal to $\sqrt{[\rho/(2\pi\omega)]}$ and that this dimension is small compared with either side of the rectangle.

Table 1

$2\sqrt{(f/R)}$	Experimental value of R_0/R	Experimental value of $R_0/R - 2\sqrt{(f/R)}$
2·63	2·77	0·14
3·03	3·14	0·11
3·39	3·47	0·08
3·72	3·76	0·04

Provided that the penetration depth is small compared with the thickness of the wall of a hollow conductor, equation (3) may be very simply modified to cover the case of hollow conductors.

Since the current only penetrates a short distance, the alternating-current resistance will be unaffected whether the central part is solid or hollow. The direct-current resistance for the hollow conductor is $1/[\beta(2 - \beta)]$ times the direct-current resistance for the solid conductor.

Equation (3) may therefore be generalized for hollow conductors by modifying it to equation (4):—

$$\frac{R_0}{R} = 2\sqrt{\left[\beta(2-\beta)\frac{f}{R}\right]} = \sqrt{\left[\frac{2\beta(2-\beta)}{\pi}\left(\frac{\omega}{R}\right)\right]} \quad (4)$$

When $\beta = 1$, i.e. for a solid conductor, equation (4) is identical with equation (3).

Table 1 shows a comparison between values of R_0/R for a solid conductor determined experimentally at the National Physical Laboratory, and values of $2\sqrt{(f/R)}$.

Experimental limitations prevented a determination of values of R_0/R higher than 3·76, but from the values in Table 1 it would appear that equation (3) is valid for all values of R_0/R greater than about 4. For this value of R_0/R the penetration depth is about 8 % of the side of the

* "Skin Effect in Rectangular Conductors at High Frequencies," *Proceedings of the Royal Society*, A, 1928, vol. 122, p. 533.
† *Philosophical Magazine*, Ser. 7, 1934, vol. 18, p. 433.
‡ *Loc. cit.*

square. The range of equation (4) for hollow conductors is dependent on the value of β, but except for very small values of β (β less than $0 \cdot 02$) the range extends at least down to values of R_0/R equal to 4. The next problem is to develop a formula for isolated conductors to cover the range of R_0/R from unity up to 4. Practical cases occur far more often in this range than in the high-frequency range covered by equation (4). The method adopted is one of successive approximations. The eddy-current distribution is first calculated on the assumption that the magnetic field due to the eddy currents may be neglected. The effect of the eddy-current magnetic field is then calculated approximately from the approximate eddy-current distribution given by the first calculation.

Assuming, then, first a uniform current density in a hollow conductor, having sides of unit length, we have

Current in filament of conductor $dx\,dy$ passing through point X $= I\,dx\,dy/[\beta(2-\beta)]$

E.M.F. induced at point P per cm. length of conductor by current in filament $dx\,dy$ passing through point X

$$= -2\omega\frac{I\,dx\,dy}{\beta(2-\beta)}\log(\text{PX})$$

$$= -\frac{\omega I}{\beta(2-\beta)}\log(x^2+y^2)\,dx\,dy$$

Total e.m.f. induced at point P per cm. length of conductor by total current in conductor uniformly distributed

$$= E_p = -\frac{\omega I}{\beta(2-\beta)}\iint^P \log(x^2+y^2)\,dx\,dy = \sigma_p\omega I \qquad (5)$$

Now, the average value of the e.m.f. induced in the conductor by a uniformly distributed current is the inductive drop at zero frequency, so that we may write

$$L\omega I = \text{average value of } E_p$$

$$= \frac{\omega I}{\beta(2-\beta)}\iint^S \sigma_p\,dp\,dq$$

The difference between the induced e.m.f., E_p at P and the inductive drop, $L\omega I$, must be absorbed by eddy currents.

As a first approximation the magnetic field of the eddy currents is neglected.

Then, eddy-current density at X

$$= (\sigma_x - L)\omega I/[R\beta(2-\beta)]$$

The e.m.f. due to the eddy currents may now be approximately calculated.

$$E_p' = -\frac{\omega^2 I}{R\beta(2-\beta)}\iint^P (\sigma_x - L)\log(x^2+y^2)\,dx\,dy$$
$$= \mu_p\omega^2 I/R \qquad (6)$$

$$\frac{\omega^2 I}{R\beta(2-\beta)}\iint^S \mu_p\,dp\,dq = l\omega^2 I/R = \text{average voltage-drop}$$

in conductor due to the magnetic field of the eddy currents. This voltage is an approximate measure of the increase of resistance-drop in the conductor due to the eddy currents.

The difference between E_p' and $l\omega^2 I/R$ is the reactance drop at P due to the eddy currents, and is in quadrature with them. The vector sum of the resistance- and reactance-drops due to the eddy currents is equal to the voltage $E_p - L\omega I$. Therefore

$$\left[i_p R\beta(2-\beta)\right]^2 + \left[E_p' - l\frac{\omega^2 I}{R}\right]^2 = \left[E_p - L\omega I\right]^2$$

$$i_p^2 = \frac{[(E_p - L\omega I)^2 - (E_p' - l\omega^2 I/R)^2]}{R^2\beta^2(2-\beta)^2}$$

Eddy-current losses in conductor

$$= \frac{\omega^2 I^2}{R\beta(2-\beta)}\iint^S\left\{(\sigma_p - L)^2 - \frac{\omega^2}{R^2}(\mu_p - l)^2\right\}dp\,dq$$

$$= \frac{\omega^2 I^2}{R}[c_1 - c_2(\omega/R)^2]$$

Then

$$R_0/R = 1 + c_1(\omega/R)^2 - c_2(\omega/R)^4 \qquad (7)$$

The reactance-drop due to the eddy currents was not calculated precisely in the development of equation (7). The exact calculation requires a series of successive approximations which would modify equation (7) to equation (8).

Table 2

β	c_1	c_2/c_1
1	0·0969	0·080
0·8	0·0804	0·062
0·6	0·0508	0·036
0·4	0·0261	0·025
0·2	0·0113	0·034
0·0	0·0062	0·061

$$R_0/R = 1 + c_1(\omega/R)^2 - c_2(\omega/R)^4 + c_3(\omega/R)^6 - c_4(\omega/R)^8 + \ldots \qquad (8)$$

The expression on the right-hand side of equation (8) forms a convergent series, but, except for small values of ω/R, the convergence is very slow and the equation is unsuitable for numerical calculation. The equation may be modified to equation (9).

$$\frac{R_0}{R} = 1 + \frac{c_1(\omega/R)^2}{\{1 + (c_2/c_1 n)(\omega/R)^2 + \ldots\}^n} \qquad (9)$$

If n is chosen suitably the convergence of the series in the denominator of equation (9) is so rapid that only the term in $(\omega/R)^2$ need be calculated in order to evaluate R_0/R within a few per cent for all values up to 4.

Equation (9) then becomes equation (10) to a close approximation.

$$\frac{R_0}{R} = 1 + \frac{c_1(\omega/R)^2}{\{1 + (c_2/c_1 n)(\omega/R)^2\}^n} \qquad (10)$$

The coefficients c_1 and c_2/c_1 have been evaluated by the method outlined in the Appendix for six values of β and are given in Table 2.

In order to be able to interpolate for intermediate values of β it is convenient to relate c_1 and c_2/c_1 to β by means of approximate equations, which have been found by a process of trial and error. These equations are

$$c_1 = \frac{1}{160} + \frac{1}{8}\beta^2 - \frac{1}{29}\beta^8 \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

$$\frac{c_2}{c_1} = \frac{1}{1\,000}\left\{61 - 185\beta + 240\beta^2 - 36\beta^9\right\} \quad . \quad (12)$$

A value of n is then adopted so that the graphs of equations (10) and (4) meet each other tangentially. Table 3 shows the necessary values of n for various values of β, together with the value $\sqrt{(\omega/R)}$ at which the graphs of equations (10) and (4) meet.

Experimental measurements have been made at the National Physical Laboratory on three sets of conductors having values of β equal to 1·00, 0·398, and 0·079 respectively.

Table 3

β	n	Value of $\sqrt{(\omega/R)}$ at which graphs of high- and low-frequency formulae meet
0·01	0·685	40
0·02	0·641	20
0·03	0·607	13·5
0·04	0·577	10·5
0·05	0·550	9·2
0·06	0·526	8·0
0·08	0·482	6·0
0·10	0·443	5·1
0·12	0·409	4·5
0·14	0·380	4·0
0·16	0·355	3·7
0·18	0·335	3·4
0·20	0·320	3·2
0·21	0·314	3·1
0·22	0·309	3·0
0·23	0·304	2·9
0·24	0·301	2·8
0·25	0·300	2·8
0·26	0·301	2·7
0·27	0·304	2·7
0·28	0·308	2·6
0·29	0·313	2·6
0·30	0·320	2·6
0·31	0·329	2·6
0·32	0·339	2·5
0·33	0·351	2·5
0·34	0·365	2·5
0·35	0·381	2·5
0·36	0·399	2·5
0·37	0·419	2·5
0·38	0·441	2·5
0·39	0·464	2·5
0·40	0·489	2·5
0·41	0·516	2·5
0·42	0·545	2·5
0·43	0·575	2·6
0·44	0·606	2·6
0·45	0·635	3·0
0·46	0·658	3·8
0·47	0·667	4·5
0·48	0·673	5·0
0·49	0·678	5·5
0·50	0·682	6·1
0·52	0·689	7·1
0·54	0·694	7·7
0·56	0·697	8·1
0·58	0·700	8·3
0·60	0·702	8·4
0·70	0·704	9
0·80	0·703	9
0·90	0·700	8·5
1·00	0·699	8

Table 4

β 1.	Equation for calculating R_0/R 2.	$\sqrt{(\omega/R)}$ 3.	Calculated value of R_0/R 4.	Measured value of R_0/R 5.	$\frac{\text{col. 5}}{\text{col. 4}}$ 6.
		0·95	1·074	1·069	$0{\cdot}99_5$
		1·35	1·257	1·253	$0{\cdot}99_7$
		1·92	1·683	1·665	$0{\cdot}98_9$
1	(10)	2·78	2·373	2·355	$0{\cdot}99_2$
		3·30	2·765	2·771	$1{\cdot}00_2$
		3·80	3·14	3·14	$1{\cdot}00_0$
		4·25	3·47	3·47	$1{\cdot}00_0$
		4·66	3·78	3·76	$0{\cdot}99_5$
0·398	(10)	0·77	1·009	1·010	$1{\cdot}00_1$
		1·09	1·035	1·035	$1{\cdot}00_0$
		1·54	1·129	1·125	$0{\cdot}99_6$
		2·25	1·441	1·426	$0{\cdot}99_0$
0·398	(4)	2·67	1·704	1·675	$0{\cdot}98_3$
		3·08	1·965	1·943	$0{\cdot}98_9$
		3·45	2·201	2·190	$0{\cdot}99_5$
		3·78	2·411	2·411	$1{\cdot}00_0$
0·079	(10)	0·465	1·000	1·001	$1{\cdot}00_1$
		0·678	1·001	1·003	$1{\cdot}00_2$
		0·927	1·005	1·006	$1{\cdot}00_1$
		1·136	1·011	1·013	$1{\cdot}00_2$

Table 4 shows a comparison between the calculated and experimental values of R_0/R. The greatest discrepancy shown is 1·7 %; and the average discrepancy, ignoring sign, is 0·4 %.

(3) PROXIMITY EFFECTS

In general, square conductors should not be placed close together, as the proximity effects are liable to be very large. If a small spacing between conductors is desired, other sections are more suitable. It is seldom, however, that the conductors of a system are placed so far apart that the proximity effects are completely negligible, and cases occasionally arise where it is

advantageous to use a square conductor even though the spacing between conductors is relatively small.

It is a simple matter to calculate the proximity losses at very low frequencies, but the problem becomes so complex at higher frequencies that experimental figures have

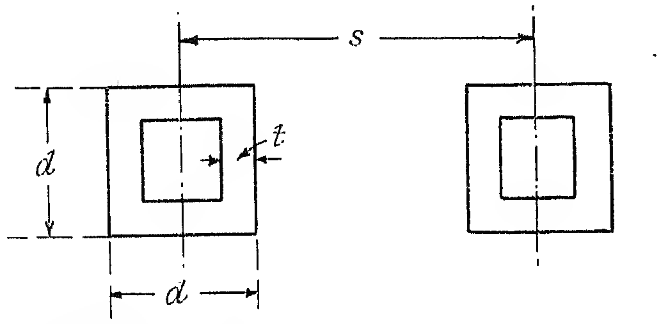

Fig. 1.—Single-phase system of two hollow square conductors. (Sectional view.)

to be used as a guide in devising a formula. In earlier papers by the author, and in the work on isolated, square conductors in this paper, experimental results have been used solely as a check on the theoretical work. The check has, however, been so close that there is little danger of serious error in a semi-empirical formula for proximity losses, although it is to be hoped that a mathematician will eventually develop a formula based on theory alone.

Two cases of proximity will be considered. The first is a system of two conductors forming a single-phase system. The second is a system of three conductors forming a 3-phase system. The conductors are assumed to be parallel, and their normal sections appear as in Figs. 1 and 2 respectively.

(a) Single-phase system of two conductors

(i) Low frequency: conductors far apart (α small).

If the conductors are far apart the return current may be assumed to be concentrated along the axis of the return conductor.

E.M.F. at P per cm. length of conductor due to current in both conductors

$$= E_p + \omega I \log \left\{(s-p)^2 + q^2\right\}$$

Average e.m.f. over conductor section $= L\omega I + \omega I \log s^2$

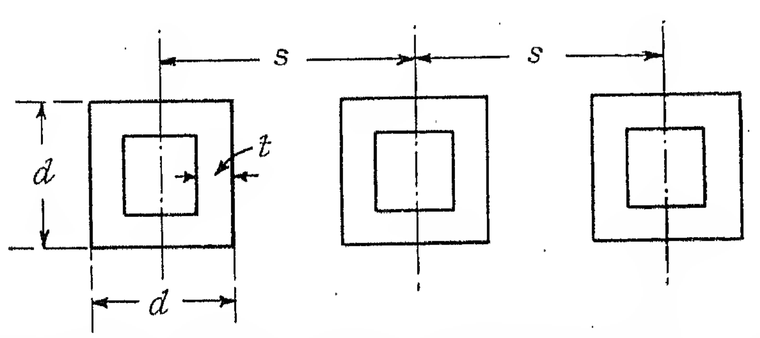

Fig. 2.—Three-phase system of three hollow square conductors. (Sectional view.)

E.M.F. at P which must be absorbed by eddy currents

$$= (E_p - L\omega I) + \omega I \log \left\{\left(1 - \frac{p}{s}\right)^2 + \left(\frac{q}{s}\right)^2\right\}$$

$$= (E_p - L\omega I) - 2\omega I p \alpha \text{ approximately} \quad . \quad (13)$$

since p and q are small compared with $s(\alpha = 1/s$, if d is taken equal to unity).

Eddy-current losses in conductor

$$= \frac{1}{R\beta(2-\beta)} \iint^{S} \left\{(E_p - L\omega I) - 2\omega I p \alpha\right\}^2 dp\, dq$$

$$= \frac{1}{R\beta(2-\beta)}$$

$$\left[\iint^{S} (E_p - L\omega I)^2\, dp\, dq + \iint^{S} 4\omega^2 I^2 p^2 \alpha^2\, dp\, dq\right] \quad (14)$$

The integral of the product term is zero. The first term in equation (14) is the amount of the eddy-current

Table 5

α	R'/R	Proximity effect	Proximity effect / $(\alpha^2\omega^2/R^2)$
0	$1+0\cdot0969(\omega/R)^2+\frac{1}{3}(\omega/R)^2\alpha^2$	$\frac{1}{3}(\omega/R)^2\alpha^2$	$0\cdot333$
$0\cdot4$	$1+0\cdot1500(\omega/R)^2$	$0\cdot0531(\omega/R)^2$	$0\cdot332$
$1\cdot0$	$1+0\cdot4074(\omega/R)^2$	$0\cdot3105(\omega/R)^2$	$0\cdot310_5$

losses in an isolated conductor, and the second term is the additional loss due to the return conductor.

$$\frac{1}{R\beta(2-\beta)} \iint^{S} 4\omega^2 I^2 p^2 \alpha^2\, dp\, dq$$

$$= \frac{4\omega^2 I^2 \alpha^2}{R\beta(2-\beta)}\left[2\int_{-\frac{1}{2}}^{-\frac{1}{2}(1-\beta)}\int_{-\frac{1}{2}}^{\frac{1}{2}} p^2\, dp\, dq + 2\int_{-\frac{1}{2}(1-\beta)}^{\frac{1}{2}(1-\beta)}\int_{-\frac{1}{2}}^{-\frac{1}{2}(1-\beta)} p^2\, dp\, dq\right]$$

$$= \frac{\omega^2 I^2 \alpha^2}{3R}\left\{2 - 2\beta + \beta^2\right\}$$

Proximity effect

$$= \frac{\text{Eddy-current losses due to return conductor}}{\text{Direct-current losses in conductor}}$$

$$= \tfrac{1}{3}\alpha^2(\omega/R)^2(2 - 2\beta + \beta^2) \quad . \quad . \quad . \quad (15)$$

Equation (15) is only valid for small values of α. For larger values it is necessary to calculate the combined losses in the conductor by the method already outlined in the case of the isolated conductor. Table 5 shows the results of these calculations for two values of α in the case of the solid conductor ($\beta = 1$).

It may be seen from Table 5 that equation (15) is substantially correct for values of α up to $0\cdot4$, but above this value the equation slightly overestimates the proximity effect.

An improved equation is obtained by writing equation (15) as

$$\text{Proximity Effect} = \frac{\omega^2 I^2 \alpha^2 (2 - 2\beta + \beta^2)}{3R(1 + \frac{1}{14}\alpha^2)} \quad . \quad (16)$$

The modification of equation (15) to equation (16) has only been checked theoretically for solid conductors and may not be strictly true for hollow conductors. The correction is, however, very small, and some error in its value is not of great importance.

Table 6

CALCULATED AND EXPERIMENTAL VALUES OF R'/R FOR SINGLE-PHASE SYSTEM OF CONDUCTORS

$\sqrt{(\omega/R)}$ 1.	Calculated value of R'/R 2.	Measured value of R'/R 3.	$\frac{\text{Col. 3}}{\text{Col. 2}}$ 4.
$\beta = 1$; $\alpha = 0 \cdot 988$.			
0·95	1·277	1·271	0·995
1·35	1·792	1·780	0·993
1·92	2·729	2·689	0·985
2·78	4·27	4·27	1·000
3·30	5·23	5·23	1·000
3·80	6·18	6·18	1·000
4·25	7·03	7·07	1·006
4·66	7·85	7·86	1·001
$\beta = 1$; $\alpha = 0 \cdot 829$.			
0·95	1·216	1·209	0·994
1·35	1·598	1·605	1·004
1·92	2·315	2·309	0·997
2·78	3·47	3·47	1·000
3·30	4·15	4·14	0·998
3·80	4·82	4·78	0·992
4·25	5·42	5·39	0·994
4·66	5·97	5·94	0·995
$\beta = 1$; $\alpha = 0 \cdot 718$.			
0·95	1·181	1·176	0·996
1·35	1·499	1·510	1·007
1·92	2·121	2·120	1·000
2·78	3·12	3·10	0·994
3·30	3·70	3·69	0·997
3·80	4·26	4·24	0·995
4·25	4·76	4·74	0·996
4·66	5·23	5·19	0·992
$\beta = 1$; $\alpha = 0 \cdot 495$.			
0·95	1·124	1·122	0·998
1·35	1·363	1·373	1·007
1·92	1·869	1·862	0·996
2·78	2·680	2·669	0·996
3·30	3·15	3·12	0·990
3·80	3·59	3·57	0·994
4·25	3·99	3·98	0·997
4·66	4·35	4·34	0·998
$\beta = 1$; $\alpha = 0 \cdot 263$.			
0·95	1·088	1·083	0·995
1·35	1·285	1·286	1·001
1·92	1·732	1·718	0·992
2·78	2·453	2·437	0·993
3·30	2·863	2·862	1·000
3·80	3·25	3·25	1·000
4·25	3·60	3·60	1·000
4·66	3·92	3·91	0·997

Table 6—*continued*

$\beta = 0 \cdot 398$; $\alpha = 0 \cdot 978$.			
0·77	1·139	1·133	0·995
1·09	1·362	1·387	1·018
1·54	1·831	1·856	1·014
2·25	2·671	2·668	0·999
2·67	3·26	3·23	0·991
3·08	3·85	3·83	0·995
3·45	4·39	4·41	1·005
3·78	4·89	4·95	1·012
$\beta = 0 \cdot 398$; $\alpha = 0 \cdot 818$.			
0·77	1·101	1·100	0·999
1·09	1·256	1·274	1·014
1·54	1·565	1·584	1·012
2·25	2·168	2·147	0·990
2·67	2·605	2·549	0·979
3·08	3·039	2·982	0·982
3·45	3·43	3·39	0·988
3·78	3·79	3·77	0·995
$\beta = 0 \cdot 398$; $\alpha = 0 \cdot 616$.			
0·77	1·061	1·061	1·000
1·09	1·157	1·169	1·010
1·54	1·351	1·358	1·005
2·25	1·798	1·771	0·985
2·67	2·139	2·090	0·977
3·08	2·477	2·426	0·979
3·45	2·783	2·752	0·989
3·78	3·06	3·04	0·993
$\beta = 0 \cdot 398$; $\alpha = 0 \cdot 336$.			
0·77	1·025	1·027	1·002
1·09	1·070	1·074	1·004
1·54	1·189	1·190	1·001
2·25	1·535	1·514	0·986
2·67	1·818	1·779	0·979
3·08	2·098	2·063	0·983
3·45	2·351	2·333	0·992
3·78	2·577	2·564	0·995
$\beta = 0 \cdot 398$; $\alpha = 0 \cdot 231$.			
0·77	1·016	1·017	1·001
1·09	1·051	1·053	1·002
1·54	1·157	1·155	0·998
2·25	1·484	1·468	0·989
2·67	1·756	1·724	0·982
3·08	2·026	2·000	0·987
3·45	2·269	2·254	0·993
3·78	2·486	2·482	0·998
$\beta = 0 \cdot 079$; $\alpha = 0 \cdot 990$.			
0·232	1·002	1·003	1·001
0·329	1·007	1·008	1·001
0·465	1·026	1·027	1·001
0·678	1·115	1·109	0·995
0·927	1·304	1·309	1·004
1·136	1·503	1·539	1·024

Table 6—*continued*

$\beta = 0\cdot079$; $\alpha = 0\cdot764$.

0·678	1·070	1·065	0·995
0·927	1·183	1·177	0·995
1·136	1·287	1·292	1·004

$\beta = 0\cdot079$; $\alpha = 0\cdot470$.

0·678	1·027	1·026	0·999
0·927	1·072	1·068	0·996
1·136	1·109	1·108	0·999

$\beta = 0\cdot079$; $\alpha = 0\cdot307$.

0·329	1·001	1·002	1·001
0·465	1·003	1·004	1·001
0·678	1·013	1·013	1·000
0·927	1·033	1·032	0·999
1·136	1·052	1·052	1·000

(ii) High frequency: conductors almost touching ($\alpha = 1$).

At very high frequencies, with the conductors almost touching, the current will be concentrated on the side of the conductor nearest to the return conductor. The distribution of the current will be substantially uniform along this surface, since the magnetic field will be the same at all parts except near the two ends. The current will penetrate the conductor to a depth of $\sqrt{[\rho/(2\pi\omega)]}$.

$$\text{Then } R' = \frac{\rho}{d\sqrt{[\rho/(2\pi\omega)]}} = \frac{1}{d}\sqrt{(2\pi\omega\rho)}$$
$$= \sqrt{[(2\pi\omega R\beta)(2-\beta)]}$$

Therefore

$$\frac{R'}{R} = \sqrt{\left[\frac{2\pi\omega\beta(2-\beta)}{R}\right]} = 2\pi\sqrt{\left[\frac{f\beta(2-\beta)}{R}\right]} \quad . \quad (17)$$

(iii) Universal formula.

It is now possible to adopt a semi-empirical formula which satisfies equation (16) at low frequencies and equation (17) at high frequencies, and which gives values in good agreement with experimental results at intermediate frequencies. This formula is set out in equation (18).

$$\frac{R'}{R} = \frac{R_0}{R} + \left[\frac{\alpha^2 A(\omega/R)}{1-\alpha^2 B(\omega/R)}\right]\left[A(\beta)\right] \quad . \quad (18)$$

R_0/R is defined by equations (4) and (10)

$$A(\omega/R) = \tfrac{1}{3}(\omega/R)^2 \text{ for values of } \omega/R \text{ less than } 0\cdot5 \quad . \quad (19)$$

$$A(\omega/R) = -0\cdot27 + \tfrac{1}{2}\sqrt{(\omega/R)} \text{ for values of } \omega/R \text{ greater than } 0\cdot5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$B(\omega/R) = \frac{1}{\sqrt{2}}\left\{\frac{20\sqrt{(\omega/R)}-3}{20\sqrt{(\omega/R)}+30}\right\} - \left\{\frac{\sqrt{(\omega/R)}}{2+2\sqrt{(\omega/R)}+(\omega/R)^6}\right\} \quad . \quad . \quad (21)$$

$$A(\beta) = \frac{(2-2\beta+\beta^2)+(\omega/R)\beta\sqrt{(2-\beta)}}{1+(\omega/R)\sqrt{\beta}} \quad . \quad . \quad (22)$$

Table 6 shows a comparison between values of R'/R calculated by equation (18) and experimental values of R'/R for three values of β. The greatest observed discrepancy is 2·4 %, and the average discrepancy, ignoring sign, is 0·6 %.

(b) Three-phase system of three conductors

(i) Low frequency: conductors far apart (α small).

Let current in middle conductor (B) $= I$
Let current in outside conductor (A) $= I(-\frac{1}{2}+\frac{1}{2}\sqrt{3}j)$
Let current in outside conductor (C) $= I(-\frac{1}{2}-\frac{1}{2}\sqrt{3}j)$

Loss in middle conductor (B).

E.M.F. at P due to conductors A and C to be absorbed by eddy currents

$$= 2\alpha\omega Ip[(-\tfrac{1}{2}+\tfrac{1}{2}\sqrt{3}j)-(-\tfrac{1}{2}-\tfrac{1}{2}\sqrt{3}j)]$$
$$= 2\sqrt{3}\alpha\omega Ip$$

$$\text{Losses in conductor B} = \frac{12\alpha^2\omega^2 I^2}{R}\iint^S p^2\,dp\,dq$$
$$= \frac{\alpha^2\omega^2 I^2}{R}(2-2\beta+\beta^2)$$

$$\text{Proximity effect} = \frac{\text{(Eddy-current losses in conductor B due to conductors A and C)}}{\text{Direct-current losses in conductor B}}$$
$$= \alpha^2(\omega/R)^2(2-2\beta+\beta^2) \quad . \quad . \quad . \quad (23)$$

Loss in outer conductor (A).

E.M.F. at P due to conductors B and C to be absorbed by eddy currents

$$= -2\alpha\omega Ip\{1+\tfrac{1}{2}(-\tfrac{1}{2}-\tfrac{1}{2}\sqrt{3}j)\}$$
$$= -\alpha\omega Ip\{3/2-\tfrac{1}{2}\sqrt{3}j\}$$

$$\text{Losses in conductor A} = \frac{3\alpha^2\omega^2 I^2}{R}\iint^S p^2\,dp\,dq$$
$$= \tfrac{1}{4}\alpha^2(\omega^2 I^2/R)(2-2\beta+\beta^2)$$

$$\text{Proximity effect} = \tfrac{1}{4}\alpha^2(\omega/R)^2(2-2\beta+\beta^2) . \quad . \quad (24)$$

Average proximity effect for the three conductors

$$= \tfrac{1}{2}\alpha^2(\omega/R)^2(2-2\beta+\beta^2) \quad . \quad . \quad . \quad (25)$$

A comparison with equation (15) of equations (23), (24), and (25), shows that at low frequencies and for small values of α the proximity effect in the middle conductor of a 3-phase system is 3 times the proximity effect in each conductor of a single-phase system, while the proximity effect in each outer conductor is $\frac{3}{4}$ of the proximity effect, single-phase.

The average proximity effect for the three conductors is 50 % greater than the single-phase proximity effect.

(ii) High frequency: conductors touching ($\alpha = 1$).

In this case, as in the single-phase system, the current in each conductor will be concentrated along the side nearest to the adjacent conductor.

For the middle conductor, the current will split up into two components equal and opposite respectively to the current in each outer conductor. The total loss in each outer conductor will therefore be the same as in the single-phase system, while the total loss in the middle conductor will be twice as large as in the single-phase system. Thus, from equation (17),

$$R'/R = 2\pi\sqrt{[f\beta(2-\beta)/R]} \text{ for each outer conductor} \quad (26)$$

$$R'/R = 4\pi\sqrt{[f\beta(2-\beta)/R]} \text{ for the middle conductor} \quad (27)$$

For the average of the three conductors,

$$R'/R = \tfrac{8}{3}\pi\sqrt{[f\beta(2-\beta)/R]} \quad . \quad . \quad . \quad (28)$$

It is permissible to split up equation (28) into components, one of which is equal to R_0/R and the balance is the proximity effect. Then

$$\begin{aligned} R'/R &= 2\sqrt{[f\beta(2-\beta)/R]} + (\tfrac{8}{3}\pi - 2)\sqrt{[f\beta(2-\beta)/R]} \\ &= 2\sqrt{[f\beta(2-\beta)/R]} + 6\cdot 38\sqrt{[f\beta(2-\beta)/R]} \quad (29) \end{aligned}$$

for the average of the three conductors of a 3-phase system, and

$$\begin{aligned} R'/R &= 2\sqrt{[f\beta(2-\beta)/R]} + (2\pi - 2)\sqrt{[f\beta(2-\beta)/R]} \\ &= 2\sqrt{[f\beta(2-\beta)/R]} + 4\cdot 28\sqrt{[f\beta(2-\beta)/R]} \quad (30) \end{aligned}$$

for each conductor of a single-phase system.

From equations (29) and (30) it may be seen that the average proximity effect in the 3-phase system is 49 % greater than the single-phase proximity effect.

It has already been shown that at low frequencies, for small values of α, the average proximity effect in the 3-phase system is 50 % greater than the single-phase proximity effect.

The percentage increase of proximity effect on the 3-phase system as compared with the single-phase system is therefore almost exactly the same at high and low frequencies, and, in default of evidence to the contrary, the same percentage may be assumed to hold at all frequencies. For the 3-phase system of conductors, therefore, the following equation may be assumed to be applicable for all values of ω/R:—

$$\frac{R'}{R} = (R_0/R) + \left[\frac{\frac{3}{2}\alpha^2 A(\omega/R)}{1 - \alpha^2 B(\omega/R)}\right] A(\beta) \quad . \quad (31)$$

It may be observed that the distribution of losses between the three conductors is not the same at low and high frequencies, and it is not possible to say what the distribution would be at intermediate frequencies.

(4) EXPERIMENTAL WORK

The method employed in obtaining accurate experimental results has already been fully described in previous papers.* The values of R_0/R given in Table 4 were obtained by extrapolating experimental curves showing the variation of R'/R with α to zero value of α. The values of R'/R given in Table 6 were actually measured values. Small corrections were made for change of resistance due to air temperature.

(5) WORKING FORMULAE

The formulae developed in this paper are gathered together here for convenient reference.

Isolated conductors.

$$\frac{R_0}{R} = 1 + \frac{\left(\frac{1}{160} + \frac{1}{8}\beta^2 - \frac{1}{29}\beta^8\right)\left(\frac{\omega}{R}\right)^2}{\left[1 + \frac{1}{1\,000n}(61 - 185\beta + 240\beta^2 - 36\beta^9)\left(\frac{\omega}{R}\right)^2\right]^n}$$

at low frequencies.

[From equations (10), (11) and (12).]

The values of n for various values of β are given in Table 3, and also the upper limit of $\sqrt{(\omega/R)}$ for which this formula is valid. Above this value of $\sqrt{(\omega/R)}$ the following high-frequency formula should be used:—

$$\frac{R_0}{R} = 2\sqrt{\left[\beta(2-\beta)\frac{f}{R}\right]} = \sqrt{\left[\frac{2\beta(2-\beta)}{\pi}\left(\frac{\omega}{R}\right)\right]} \quad (4)$$

Single-phase system of two conductors.

$$\frac{R'}{R} = \frac{R_0}{R} + \left[\frac{(2-2\beta+\beta^2) + (\omega/R)\beta\sqrt{(2-\beta)}}{1 + (\omega/R)\sqrt{\beta}}\right]\left[\frac{\alpha^2 A(\omega/R)}{1 - \alpha^2 B(\omega/R)}\right]$$

[From equations (18) and (21).]

Three-phase system of three conductors.

Average value of

$$\frac{R'}{R} = \frac{R_0}{R} + \left[\frac{(2-2\beta+\beta^2) + (\omega/R)\beta\sqrt{(2-\beta)}}{1 + (\omega/R)\sqrt{\beta}}\right]\left[\frac{\frac{3}{2}\alpha^2 A(\omega/R)}{1 - \alpha^2 B(\omega/R)}\right]$$

[From equations (29) and (21).]

$$A(\omega/R) = \tfrac{1}{3}(\omega/R)^2 \text{ for values of } (\omega/R) \text{ less than } 0\cdot 5 \quad (22)$$

$$A(\omega/R) = \tfrac{1}{2}\sqrt{(\omega/R)} - 0\cdot 27 \quad \text{for values of } (\omega/R) \text{ greater than } 0\cdot 5 \quad (19)$$

$$B\left(\frac{\omega}{R}\right) = \frac{1}{\sqrt{2}}\left[\frac{20\sqrt{(\omega/R)} - 3}{20\sqrt{(\omega/R)} + 30}\right] - \left[\frac{\sqrt{(\omega/R)}}{2 + 2\sqrt{(\omega/R)} + (\omega/R)^6}\right] \quad . \quad (20)$$

* *Journal I.E.E.*, 1935, vol. 77, p. 49; and 1936, vol. 78, p. 580.

APPENDIX

Evaluation of Coefficients c_1 and c_2 (See Table 2)

$$
\begin{aligned}
-\sigma_p\beta(2-\beta) &= \iint^P \log (x^2 + y^2\, dx\, dy \\
&= (\tfrac{1}{2}+p)(\tfrac{1}{2}+q)\log\left[(\tfrac{1}{2}+p)^2+(\tfrac{1}{2}+q)^2\right] + (\tfrac{1}{2}+p)(\tfrac{1}{2}-q)\log\left[(\tfrac{1}{2}+p)^2+(\tfrac{1}{2}-q)^2\right] \\
&\quad + (\tfrac{1}{2}-p)(\tfrac{1}{2}+q)\log\left[(\tfrac{1}{2}-p)^2+(\tfrac{1}{2}+q)^2\right] + (\tfrac{1}{2}-p)(\tfrac{1}{2}-q)\log\left[(\tfrac{1}{2}-p)^2+(\tfrac{1}{2}-q)^2\right] \\
&\quad + (\tfrac{1}{2}+p)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+q}{\frac{1}{2}+p}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-q}{\frac{1}{2}+p}\right)\right] + (\tfrac{1}{2}-p)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+q}{\frac{1}{2}-p}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-q}{\frac{1}{2}-p}\right)\right] \\
&\quad + (\tfrac{1}{2}+q)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+p}{\frac{1}{2}+q}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-p}{\frac{1}{2}+q}\right)\right] + (\tfrac{1}{2}-q)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+p}{\frac{1}{2}-q}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-p}{\frac{1}{2}-q}\right)\right] \\
&\quad - (\tfrac{1}{2}+p-\tfrac{1}{2}\beta)(\tfrac{1}{2}+q-\tfrac{1}{2}\beta)\log\left[(\tfrac{1}{2}+p-\tfrac{1}{2}\beta)^2+(\tfrac{1}{2}+q-\tfrac{1}{2}\beta)^2\right] \\
&\quad - (\tfrac{1}{2}+p-\tfrac{1}{2}\beta)(\tfrac{1}{2}-q-\tfrac{1}{2}\beta)\log\left[(\tfrac{1}{2}+p-\tfrac{1}{2}\beta)^2+(\tfrac{1}{2}-q-\tfrac{1}{2}\beta)^2\right] \\
&\quad - (\tfrac{1}{2}-p-\tfrac{1}{2}\beta)(\tfrac{1}{2}+q-\tfrac{1}{2}\beta)\log\left[(\tfrac{1}{2}-p-\tfrac{1}{2}\beta)^2+(\tfrac{1}{2}+q-\tfrac{1}{2}\beta)^2\right] \\
&\quad - (\tfrac{1}{2}-p-\tfrac{1}{2}\beta)(\tfrac{1}{2}-q-\tfrac{1}{2}\beta)\log\left[(\tfrac{1}{2}-p-\tfrac{1}{2}\beta)^2+(\tfrac{1}{2}-q-\tfrac{1}{2}\beta)^2\right] \\
&\quad - (\tfrac{1}{2}+p-\tfrac{1}{2}\beta)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+q-\frac{1}{2}\beta}{\frac{1}{2}+p-\frac{1}{2}\beta}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-q-\frac{1}{2}\beta}{\frac{1}{2}+p-\frac{1}{2}\beta}\right)\right] \\
&\quad - (\tfrac{1}{2}-p-\tfrac{1}{2}\beta)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+q-\frac{1}{2}\beta}{\frac{1}{2}-p-\frac{1}{2}\beta}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-q-\frac{1}{2}\beta}{\frac{1}{2}-p-\frac{1}{2}\beta}\right)\right] \\
&\quad - (\tfrac{1}{2}+q-\tfrac{1}{2}\beta)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+p-\frac{1}{2}\beta}{\frac{1}{2}+q-\frac{1}{2}\beta}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-p-\frac{1}{2}\beta}{\frac{1}{2}+q-\frac{1}{2}\beta}\right)\right] \\
&\quad - (\tfrac{1}{2}-q-\tfrac{1}{2}\beta)^2\left[\tan^{-1}\left(\frac{\frac{1}{2}+p-\frac{1}{2}\beta}{\frac{1}{2}-q-\frac{1}{2}\beta}\right)+\tan^{-1}\left(\frac{\frac{1}{2}-p-\frac{1}{2}\beta}{\frac{1}{2}-q-\frac{1}{2}\beta}\right)\right] \\
&\quad - 3\beta(2-\beta) \qquad \qquad (32)
\end{aligned}
$$

The value of σ_p may be evaluated from equation (32) for any values of p and q and for any value of β. This is as far as it is practicable to proceed by rigid mathematics, and further progress is made by approximate integration. σ_p is evaluated, for any given value of β, for a large number of values of p and q. From the values so obtained, the value of the integral $\frac{1}{\beta(2-\beta)}\iint^S \sigma_p\, dp\, dq = L$ is determined by approximate integration, employing Simpson's rule. Finally, the coefficient c_1 is determined in a similar manner by evaluating approximately the integral $\frac{1}{\beta(2-\beta)}\iint^S (\sigma_p - L)^2\, dp\, dq.$

The coefficient c_2 is evaluated in a similar manner to the coefficient c_1, but in this case it is not possible to perform even the first integration by rigid mathematics. The first expression to be integrated by approximate integration is

$$\frac{1}{\beta(2-\beta)}\iint^P (\sigma_x - L)\log (x^2+y^2)\, dx\, dy$$

This expression contains an infinite point, $x = 0$, $y = 0$, and at this point the rules for approximate integration cannot be applied. The difficulty is overcome by substituting a simple expression for the true expression which is valid near the origin and which can be integrated.

Thus, let $(\sigma_x - L) = A$ when $x = 0,\ y = 0$
let $(\sigma_x - L) = B$ when $x = \tfrac{1}{2}\delta,\ y = 0$
let $(\sigma_x - L) = C$ when $x = \delta,\ y = 0$

where δ is a small value of x.

Assuming, that in the range of x between zero and δ, the values of $(\sigma_x - L)$ may be represented by a parabola. Then,

$$(\sigma_x - L) = A + (4B-3A-C)(x/\delta) + (C+A-2B)(2x^2/\delta^2)$$

$$
\begin{aligned}
\int_0^\delta (\sigma_x - L)\log x^2\, dx &= \int_0^\delta \Big[A + (4B-3A-C)(x/\delta) \\
&\qquad + (C+A-2B)(2x^2/\delta^2)\Big]\log x^2\, dx \\
&= 2\delta\Big[A\{(\log\delta)-1\} + \tfrac{1}{2}\{4B-3A-C\}\{(\log\delta)-\tfrac{1}{2}\} \\
&\qquad + \tfrac{2}{3}\{C+A-2B\}\{(\log\delta)-\tfrac{1}{3}\}\Big] \qquad (33)
\end{aligned}
$$

The remainder of the integration by Simpson's or the three-eighths rule is quite straightforward.

In evaluating c_1 and c_2 the interval between successive values of the function to be integrated approximately was taken as $0 \cdot 05$ where the side of the square is unity and the value of δ was taken as $0 \cdot 1$. For $\delta = 0 \cdot 1$, equation (33) becomes equation (34).

$$
\begin{aligned}
\int_0^{0\cdot 1} (\sigma_x - L)\log x^2\, dx = &-0\cdot 66052A - 0\cdot 28026(4B-3A-C) \\
&- 0\cdot 3514(C+A-2B) \qquad (34)
\end{aligned}
$$

DISCUSSION ON

"RECENT DEVELOPMENTS IN TELEGRAPH TRANSMISSION, AND THEIR APPLICATION TO THE BRITISH TELEGRAPH SERVICES"*

WESTERN CENTRE, AT GLOUCESTER, 13TH DECEMBER, 1937

Mr. G. R. Tamplin: The authors refer to the introduction of "ancillary" facilities at head offices to improve operating conditions. At the Bristol head office, 85 lines are dealt with at 20 ancillary positions. Under the original conditions these lines would have demanded 85 teleprinters. The economies in instrument and operating costs, together with the employment of automatic answer-back signals from the "out" offices, enable telegraph offices to be maintained at smaller places where the amount of traffic would not otherwise justify their employment.

The conveyor band system used in head offices provided an interesting problem in elementary science, in that static electrification of the belts in dry weather caused telegraph forms to adhere. The difficulty was combated by, amongst other means, the use of a steam kettle to introduce moisture in dry weather, and was finally cured by employing a belt with interwoven metallic strands.

Mr. H. W. Gifford: Will the authors inform me why it was necessary some time ago to spend at least half an hour each morning on "lining up" the equipment at Milford Haven prior to the day's traffic? As the power plant was running continuously the plant ought to have been sufficiently stable for this to be obviated. The circuits too were often transferred to the physical conductors, presumably on account of distortion. Trouble was also experienced at Haverfordwest, but it is understood that greater stability has been achieved with the present-day equipment. So far as the Gloucester section is concerned, we have a 4-channel system working from Cheltenham, and very little trouble has been experienced at that office.

It speaks well for the training staff at Dollis Hill that after a few months' training at headquarters new recruits to the Department can efficiently maintain this very intricate and costly apparatus, which, to those who were closely associated with duplex, quadruplex, and Wheatstone working, is the greatest achievement in the history of telegraph communication.

Col. H. Carter: The paper describes a change in the telephone and telegraph systems of the British Post Office which may perhaps be described as analogous to changing over a grid transmission system which attempted to transmit that part of its load which is required for lighting by direct current and the remainder by alternating current to a wholly a.c. transmission system.

A noteworthy part of the change has been the complete elimination of the use of the Morse Code. I should like to ask the authors whether the development of small synchronous motors is likely to be of any assistance in the working of the teleprinter system.

Finally, it would be of interest to know what progress had been made in the study of the automatic switching problem since the paper appeared in the *Journal*.

Messrs. L. H. Harris, E. H. Jolley, and F. O. Morrell (*in reply*): Some economy in apparatus and operating costs have resulted, as Mr. Tamplin states, from the introduction of "ancillary" working, and this has enabled teleprinter working to be justified at telegraph offices where formerly the telegrams were disposed of by telephoning to the head office.

In reply to Mr. Gifford, the voice-frequency equipment does not normally require any preliminary "lining-up" such as he refers to, and it works for long periods without re-adjustment. It is thought that there may have been some early troubles at Milford Haven due to the fact that the plant was installed at extremely short notice when it was decided, as a result of a serious storm breakdown, not to restore the overhead route but to lay underground cables. Also, in the early stages an alternative 4-wire circuit was not available and a failure of this circuit involved a return of the telegraph circuits to physical conductors.

In reply to Col. Carter, progress in the design of a synchronous motor specially adapted for the teleprinter has been made and it is hoped ultimately to use these motors at out-offices where a frequency-controlled alternating-current supply is available.

With regard to the reference to automatic teleprinter switching, it can be said that successful field experiments have now been carried out which have demonstrated the practicability of the proposed methods of interconnecting teleprinters for the transmission of telegrams direct to the office of destination

* Paper by Messrs. L. H. Harris, E. H. Jolley, and F. O. Morrell (see vol. 80, p. 237).

DISCUSSION ON
"FIRE PRECAUTIONS IN MAJOR ELECTRICAL STATIONS"*

SCOTTISH CENTRE, AT EDINBURGH, 26TH OCTOBER, 1937

Mr. E. Seddon: The paper is timely because the very serious fire which occurred last year in the switch-house of a Yorkshire municipal power station has focused the attention of power-station engineers on the suitability of their own appliances for dealing with similar fires which may occur on plant under their charge.

We must do everything we can to prevent the spread of fire, from whichever source it comes, by isolating as far as possible each section of plant from its neighbour.

In selecting apparatus for extinguishing fires we are confronted with so many different types of appliances that we are apt to be confused as to the most suitable plant to install, and I think we need some lead from a responsible authority on this matter.

Referring to switchgear fires, I do not think we power-station engineers pay sufficient attention to the protection of cables inside the power house. In a recent extension of switchgear in Edinburgh we have tried to improve on the old methods by laying the high-voltage cables in sand troughs below the switchgear; and where cables rise into the switch-room we are building around the cables brick compartments filled with sand up to a point immediately below the cable boxes. Also, in the case of the main switchgear we have a graded floor with a 6-in. drain pipe below each switch unit. In addition to these precautions fixed pipes conveying fire-foam, operated from the floor beneath, can be brought into use in case of fire.

If I were about to design a new power station I should seriously consider the complete elimination of all primary switchgear from the power house by installing the alternator switches in the major substations. Besides having the advantage of reducing fire risks, this scheme would save a good deal of capital expenditure on switchgear.

The author makes only a brief mention of the risks of fire from lubricating oil. It is well known that a leaky oil pipe over a high-temperature steam pipe may cause a disastrous fire, and we have done our best to reduce risks of this nature by installing large mild-steel trays below the oil-storage tanks and having a large pipe connection from these trays to the drain. In spite of all the precautions we may take in this direction, however, the possibilities of fire in various forms have to be reckoned with, and it is essential that we provide fire-fighting apparatus to cope with any emergency.

Mr. W. J. Cooper: The author mentions the stability and suitability of outdoor-type switchgear so far as fire protection is concerned. This seems to indicate that he feels that the industry will be forced to adopt a unit-type construction, forgetting entirely the practice of trying to bring all our switches and cables into confined areas within a building. I imagine that in the power station and major substation of the future the important component parts of the plant will be separated in one of the ways suggested by the author, and perhaps the separation may even be carried much farther—into separate buildings: in this case, not only would there be a physical barrier between the plant items but there would be a space between the buildings containing the unit-type construction.

I agree with him that technical perfection and reliability are probably only limited by what is rather vaguely called "practical economics," and it seems to me that practical economics is just a question of length of view.

Mr. Norman C. Bridge: I agree in general with most of the author's contentions, but when he advocates duplication as a fire precaution I feel that this may be going a little too far. Duplication by all means for service purposes, where this is economically justified, and also segregation up to a point, but duplication merely as a fire precaution would seem to be an unjustified extravagance. Bearing in mind the high initial cost of modern power-station switchgear, it is surely better to devote the whole of the money available to single gear of undoubted dependability.

Regarding the question of the oil risk on generating sets, to which Mr. Seddon has referred, I am sorry to see that he has his oil tank right up against the machine. With the latest plant in one of the power stations in the West in which I am interested, we have prevailed upon the manufacturers to keep the oil tanks right away from the machines, and I imagine that this will become the regular practice.

There is just one other point I would mention, and that is the question of switch-house heating and ventilation. To ensure dry gear, movement of the air may be of even more value than heating, but segregation of the gear carried to any considerable extent would seem to imply a multiplicity of ventilating outfits. This is not very economical, and I should like to ask how the author would propose to meet the point.

Mr. J. Eccles: The first important point made by the author is the relative infrequency of fires in major electrical stations. He describes it as a 100-year emergency; and I think an insurance company would be willing to cover such a risk for an almost negligible premium. We should not, therefore, get our ideas out of proportion, but must remember that we are dealing with a very small risk in terms of ordinary operation.

* Paper by Mr. F. C. WINFIELD (see vol. 81, p. 289).

The author's next important point is that the switchgear, being the nerve centre of the station, is the vital plant from the fire-protection point of view. Not only is the supply to the local system involved, but, in the case of power-station switchgear at any rate, the supply to or from the grid is also jeopardized by a fire in the main switch-room. One may take certain risks with individual generators, in the full knowledge that the grid supply is there to give at least a skeleton service until repairs can be effected; but where there is only a single switch-room we know from experience in this and other countries how disastrous the consequences of a switch-room fire can be. The switch-rooms of the future will no doubt be separated not only from each other but from the power station itself, and one can conceive of the future power station comprising a main building for the plant and a series of lodges near the entrance gate for the switchgear. I am not sure whether the author intends to recommend CO_2 as a means of extinguishing fires, but it is a fact that if the explosion is sufficiently violent to blow out windows or doors, as is contemplated in another section of the paper, then the efficiency of the CO_2 equipment is somewhat impaired. The author recommends, I think rightly, the maintenance of the switch-room temperature at a fairly high even value from the point of view of elimination of moisture; but how can this recommendation be applied economically in semi-outdoor installations in which the circuit breaker is exposed to the weather and the control room is under cover?

Has the author yet come to a decision as to whether or not to protect busbars? If one takes reasonable precautions in the scheme of protection, in the apparatus itself, and in the manner of installation, the risk of inadvertent operation should be slight, and in my experience the cost of simple apparatus is a very small percentage of the first cost of the switchboard. A point not mentioned in the paper is that communication circuits should not pass through the switch-room. One of the most essential points during or after a breakdown is to be able to establish communication by telephone, and in a great number of instances of which I have knowledge the telephone lines pass through the switch-room to the exchange.

The question of lubricating oil has been touched upon, and the difficulties in this connection are very real. On new designs why should not the oil tank and pump be located at the alternator end of the set, beyond the exciter? The lubricating system would operate just as effectively if this were done, and the installation would be much safer than those in which the tank, containing up to 2 000 gallons of oil, is placed adjacent to steam pipes at the governor end. The views of turbine manufacturers on this suggestion would be of value.

Mr. J. E. Bell: I am thoroughly in accord with the recommendations of the author regarding separation of the different sections of a power station. In my work on behalf of an insurance company I have been struck by the remarkable improvement in power-station risks during the last 25–30 years. When I remember what the older stations were like, I wonder that there were not more fires. I remember one instance where the switchboard was a large wooden board fed from the accumulators. When a fire took place, nothing could be done to cut off the curent: the firemen turned the hose on to the fire, but it had to burn itself out. Another fire in more recent days emphasized the importance of sectional arrangement and isolation of the building containing the oil tanks. In this case the entire station consisted of a large shed, and three of the oil tanks burst and set fire to other tanks, in consequence of which there was a serious fire. The heat was so intense that a ferro-concrete roof was very badly damaged, and had to be replaced.

I should like to know the author's views on the question of fires in power stations caused through lightning.

Regarding the rate for insurances, this is very moderate, possibly owing to competition. The rate is not very different from that for the fire insurance of dwelling-houses.

Mr. D. M. Macleod: The author gives the risk of fire or explosion in major electrical stations as a 100-year emergency, but I am afraid he must amend that figure to-day, in view of the possibilities of hostile aircraft attacking this country. Electricity has now become such an important communal service that it would in all probability be their aim to put our power stations out of service altogether. Many power stations are alongside rivers, and, as nothing is easier to spot from the air than a river, I think we shall need to revise our ideas entirely as to the protection to be afforded these stations so as to prevent their being put out of service for indefinite periods. One of the things we have to do is to eliminate, so far as we can, those risks which tend to interrupt the service for prolonged periods.

The author refers to air-blast circuit-breakers as providing added safety, and this point is well worth the consideration of all power engineers. The use of this type of circuit-breaker has become standard practice on the Continent. We cannot very well eliminate oil from our transformers, but we ought to consider the question of placing our transformer equipment out of doors.

In connection with one of his slides the author called attention to the carbon-dioxide fire-extinguishing equipment; this seems to me to offer the best means for fighting fire. It is an established fact that air containing 15–20 % of carbonic-acid gas will not support combustion, and it is a simple matter to ensure that a confined space is flooded with carbonic-acid gas. Cases can even be cited where carbonic-acid gas has been applied with success to outdoor transformer equipment. In such cases one must use a higher relative proportion of CO_2.

On page 295 the author does less than justice to the engineers who design our power stations, when he visualizes a burst oil pipe under pressure, with leaking oil coming into contact with heated pipes, presumably steam pipes. I cannot imagine any responsible engineer neglecting the elementary duty of seeing that his pipelines have been suitably pressure-tested and that all his steam pipes have been properly lagged.

Mr. J. Gogan: There is an aspect of the paper and the discussions that have taken place elsewhere which has not been mentioned by previous speakers, and that is the kVA rupturing capacity of the switches. The majority of fires are the result of explosions following the failure of oil switches to deal with short-circuits, and it is probable that the failure of these oil switches is due to the growth of the system or systems without a corresponding increase in the rupturing capacity of the

switches. It is the modern practice to test to destruction oil switches of a given design or type, and these tests are not going to be of great value if the supply undertakings have to have, in addition, expensive layouts to deal with fire risks. I should be glad to have the author's observations on this point.

Mr. J. Hagen: Before coming to Edinburgh I had experience of a disastrous explosion in which, although a window was blown out into the street, fortunately no fire occurred. But for that window taking the force of the explosion, I fear that something worse might have happened.

Has the author had any experience with regard to the fire-foam equipment which can be carried on a man's back and which can give a jet of about 50 ft.? Would this be a successful piece of mechanism to carry in the power station?

The segregation of oil tanks is a very useful fire precaution. I understand that at a certain power station in Scotland all the turbines take their oil from one system, and I think there is a lot to be said for that arrangement. The disadvantage is, however, that acidity may occur in one set and contaminate the whole system.

The author says that water-spraying for transformer fires is useful, but I am rather concerned in regard to this where transformers are closely adjacent to each other and it is almost impossible to segregate them. In the event of a fire, would an automatic water spray meet such a case, if one could prevent the spray directed at one transformer from affecting the adjacent one?

A practice which I regard as dangerous is that of giving out boiling-plate cooking apparatus indiscriminately to power-station staffs, and allowing men to cook just where they find it most suitable. The use of the open type of cooking-plate in any part of the station should be debarred, and all heating done by means of tubular heaters.

Prof. M. G. Say: Will the author be good enough to give us some details regarding Doble testing?

Mr. F. C. Winfield (*in reply*): A number of points raised in this discussion are similar to those raised at other Local Centres or have at any rate been dealt with in my replies at those Centres; I shall therefore confine my further comments as far as possible to new points.

Mr. Seddon appears to have made excellent arrangements for cable protection, which require no comments except the warning that it is desirable to watch cable-heating conditions when applying heat insulation to cables. Where only short lengths of a foot or so are heat-insulated the end effect is sufficient to prevent overheating of the cables, but if long lengths are heat-insulated it may be necessary to provide additional copper section.

Mr. Seddon's suggested scheme of elimination of power-station switchgear is an attractive one which, in fact, has been considered several times in respect of the reduction of concentration of fault kVA. Actually there are a number of practical difficulties which make it difficult to apply, particularly in respect of busbar facilities, control, economy of operation, and disposition of spare plant. The present expression of this outlook is really found in the urge for small dispersed power stations which has arisen from air-raid considerations; the latter are in many ways akin to fire-risk considerations.

I agree with Mr. Seddon that it is impossible at present to eliminate entirely the fire risk from turbine lubricating-oil, and the ultimate precautions can only be fire division and fire-fighting equipment.

In reply to Mr. Bridge, it is pointed out in the paper that the duplication and segregation of electrical duplicates in groups is generally accepted practice, and it is suggested that to extend such segregation to the physical sphere is merely logical. It is also pointed out that complete dependence on the reliability of " single gear " as he and Mr. Logan appear to suggest, is a counsel of perfection. Mr. Bridge's and Mr. Eccles's suggestion that turbine oil-tanks should be remote from the turbine is a sound step in the right direction but does not, of course, cover the usual failure of pipe connections.

As to ventilation, I would point out that I do not suggest a multiplicity of segregated units but as few as possible. Ventilation or heating will be found to be a small item of cost with reasonable segregation. After all, to install the same amount of gear in two half-size buildings instead of one large building does not imply a great addition to heating or ventilation requirements.

I am glad to note Mr. Eccles's general agreement with some important principles in the paper. The series of dispersed buildings he visualizes in the future is being approached to a considerable extent at present as a result of air-raid requirements.

The explosion risk where CO_2 is installed is a live point on which we lack actual experience. However, briefly this possibility is taken care of by allowing a large excess of CO_2 and a spare charge plus careful arrangement, in which the CO_2 is largely applied to produce a blanket direct on to the gear just as if the job were an outdoor one. It will be remembered in this connection that the CO_2 is discharged under considerable pressure. For semi-outdoor gear ventilation must be relied on as for outdoor gear in order to reduce condensation, but, generally, increased maintenance and a more careful supervision are necessary.

Respecting the protection of busbars, my feeling is as before to proceed with carefully chosen applications and to await experience. I refer to the low cost of *simple* apparatus. This is surely the core of the matter, since the apparatus in practice proves anything but simple.

I am glad to note Mr. Bell's comments from the insurance-company standpoint on the great reduction in fire risk which has taken place and the low premiums required. I myself cannot recall any example of a power-station fire caused by lightning.

I agree with Mr. Macleod that air attack introduces an important modification in outlook. Broadly, all the suggested fire precautions apply, but the emphasis must lie here on physical separation of groups, since explosion is the real enemy, particularly with enclosed gear where the thermite bomb precaution is an external measure.

I would remind Mr. Bell, in his remarks about suitable lagging of hot places on turbines, of the incidents at Brussels, Portishead, and elsewhere.

I have seen many successful experimental demonstrations with the type of portable equipment described by Mr. Hagen, and I consider that some such apparatus should always form part of the equipment of a power station.

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 16TH NOVEMBER, 1937

Mr. F. H. Whysall: The earliest recollections that I have of fire dangers in power stations are centred on very large culverts containing the main l.t. feeders to a town or city. The cables were clamped on the sides and roof of a concrete culvert, which formed an excellent flue in the event of a fire. As far as my personal experience is concerned the fires which occurred were put out in their very early stages by means of appliances which are only suitable for tiny fires.

When I was in Manchester, owing to contacts which I had made with a German firm I conceived the notion more than 30 years ago of using CO_2 protective measures. I took a long strip of hoop iron, bent it in steps, placed it within a large wooden box with a plate-glass front, and on each step placed an inch of lighted candle. I then released the gas inside the box to demonstrate to the city electrical engineer how the candles were quickly extinguished as the gas rose. He was very much afraid of this deadly gas and refused to consider the proposal which I put before him. He solved the problem by building walls at intervals along the culvert and packing all the cables with asbestos so that there could not be any flue effect if a fire occurred, and all such fires could be isolated.

The author insists on the value of rubble as a fire precaution, and I should like to say that in all our new works on the Belfast system we have made arrangements for any leakage of oil to drain away through rubble or gravel. Certain of our substations give us cause for concern from the fire-risk point of view, and we are quite willing to spend money on bringing them up to date, but sometimes we meet with opposition from our consumers. We keep before us above all the importance of continuity of supply.

Mr. F. W. Parkinson: The author favours the use of steel beams in building construction. While steel is clearly necessary for central-station construction, for substations reinforced concrete is surely preferable. A reinforced-concrete building is as nearly fireproof as possible, whereas steel beams are a source of weakness.

Mr. F. Johnston: I should like to know why the author is so severe in his criticism of aluminium, seeing that both aluminium and iron would be likely to melt in an oil flame.

He refers to a $\frac{3}{4}$-in. layer of sprayed asbestos. How is this material sprayed on?

I should also like to know something more about the Doble system of testing. Most fires are caused by breakdown of insulation, and the difficulty has been in making insulation tests not from one or other side of the installation to earth but from pole to pole. Does the Doble system take this into account, and does it enable one to measure the insulation resistance between poles without shutting down the system?

Mr. E. N. Cunliffe: It would appear that for the purposes of the paper a major electrical station is one which controls both legs of a duplicate feed to any town or district to which there is no other adequate means of supply. In the event, therefore, of the destruction of the station by fire, explosion, or bombing, there would be a total shutdown of supplies to the district for a period too long to be contemplated. I should be interested to know whether this description approximates to the author's own definition of a major electrical station.

There can be no doubt that for stations of this type the maximum precautions against fire should be adopted. In many cases it would be an advantage if duplicate transformer substations were split completely into halves, interconnected by cabling, and situated a few hundred feet apart, thereby feeding the lower-voltage network at two distinct and separate points. Such an arrangement should be completely immune from all possible risks, and I do not think the cost would be very much greater than that of the ordinary arrangement. The two small sites required might even be easier to find than a single site of the usual large dimensions.

Here in Belfast the majority of the recommendations put forward by the author are rapidly being put into effect. In all new substations from the largest step-down type to the smallest distribution type it has for some time past been standard practice to accommodate the switchgear and transformers in separate fireproof compartments, in each of which oil-drainage sumps of adequate capacity are formed. Special attention has been paid to substations on consumers' premises where the spread of an oil fire from the substation to the main buildings might involve disastrous losses, and every practicable precaution has been adopted in an attempt to make these substations safe. In the older type of rotary-convertor substation, however, the problem is more difficult as the plant does not always lend itself to ready subdivision. In such cases the transformers are being surrounded by dwarf brick walls, and oil-drainage pebble beds are being formed in cable trenches and other necessary places.

I agree with the author that fires in cable chambers are very rare. It is, however, possible for such fires to occur, and in this connection I would draw attention to a combination of circumstances which once nearly led to a disastrous fire. A 3-phase short-circuit occurred at the end of a long length of h.t. cable which was supported on cleats along the cable chambers and the walls of the station. The section of the cable was small, and the available fault power heavy; the switch failed to open, with the result that the cable was completely destroyed and set on fire at numerous points along the route, even though the circuit was finally cleared elsewhere after 2–3 sec. This shows that in stations of large capacity the cross-section of all h.t. cables should be made comparatively large, even if the cable is only intended for light duty. I should be interested to know whether the author is in favour of providing any form of automatic fire-extinguishing equipment for cable chambers or for cables racked in groups along station walls.

Apparently the majority of switchgear fires are accompanied by explosions of a violent nature which sometimes damage or destroy the building. This leads to the question of how far it is safe to subdivide the smaller switch-rooms into still smaller compartments, since by this means the "air-cushioning" effect is being decreased with consequent risk of building collapse. I should like to have the benefit of the author's experience in this respect.

Mr. J. A. C. King: I should like to ask the author to explain more fully his particular method of extinguishing an oil fire. I understand that he favours draining the oil into pits; is there not a danger of the water falling into the rubble-filled pit and floating out the oil, thus adding fuel to the fire from below as well as from above?

I read of a case recently where a large supply of oil, presumably from an oil tank, broke loose during a fire and found its most reasonable outlet in following the course of a river through a large town. The oil caught fire and turned the river into a sea of flame. A reinforced-concrete bridge was literally pulverized by the heat. Is there not a similar risk of serious damage where concrete is present in a substation?

Mr. F. C. Winfield (*in reply*): I note Mr. Whysall's experience with fire in a cable culvert. My own view is that with modern lead-covered cables, provided all waterproofing is stripped back and all other fire-supporting matter excluded, the likelihood of serious fire arising inside a culvert is very small indeed.

I would remind Mr. Parkinson that the paper advocates *protected* steel or reinforced concrete.

In reply to Mr. Johnston, in every serious oil fire I know of where there has been exposed aluminium this has disappeared in the fire, usually allowing more compound or oil to join the conflagration. I cannot recall an instance in which in modern metalclad gear a fire has produced serious permanent damage to panels other than the faulty one except in this single particular. Hence I recommend the elimination of exposed aluminium as an enclosure for oil or compound. Sprayed asbestos is applied with a spraying gun similar to a cement gun. The Doble test can be applied from pole to pole where necessary, but the bulk of requirements are covered by testing insulation to earth.

Mr. Cunliffe's arrangement really amounts to carrying out the physical division suggested in the paper to its fullest extent by building two supporting substations instead of a single divided substation. This arrangement is, of course, very sound and the points remaining to be treated locally in such an arrangement will be the actual source point of supply and the lower-voltage network.

I am glad to note his general agreement with the points made in the paper, as exemplified by his practice. I do not quite follow his reference to making use of cables of large section, since if a switch fails to trip, the burn-out of a cable may be expected whatever its section, within reason. Given at least one physical division in the cable arrangements and the exclusion of all external combustible matter, it is not my opinion that permanent fire-extinguishing equipment is necessary for cable chambers. It is only rarely that switch failures are accompanied by explosion of a type liable to damage building structure, but I agree with Mr. Cunliffe that very small buildings might well be enlarged somewhat to increase the cushioning effect. At the same time I do not think that the type of secondary explosion which usually produces building damage has a very steep wave-front. Hence I favour relief arrangements in the form of window space.

In reply to Mr. King, whenever necessary free-drainage facilities must be provided in exposed sumps. If the site high-water level is high the sumps can be erected above ground-level so as to facilitate drainage.

Regarding damage to concrete structures by fire, it must be realized that all constructions have a limited fire life, 15 minutes, 30 minutes, 1 hour, 2 hours, or 4 hours. Hence fire-fighting arrangements are an essential feature of any full scheme. Practice would indicate that $\frac{1}{2}$-hour to 1-hour fire resistance meets the usual case reasonably.

NORTHERN IRELAND SUB-CENTRE, AT BELFAST, 16TH NOVEMBER, 1937

Mr. F. H. Whysall: The earliest recollections that I have of fire dangers in power stations are centred on very large culverts containing the main l.t. feeders to a town or city. The cables were clamped on the sides and roof of a concrete culvert, which formed an excellent flue in the event of a fire. As far as my personal experience is concerned the fires which occurred were put out in their very early stages by means of appliances which are only suitable for tiny fires.

When I was in Manchester, owing to contacts which I had made with a German firm I conceived the notion more than 30 years ago of using CO_2 protective measures. I took a long strip of hoop iron, bent it in steps, placed it within a large wooden box with a plate-glass front, and on each step placed an inch of lighted candle. I then released the gas inside the box to demonstrate to the city electrical engineer how the candles were quickly extinguished as the gas rose. He was very much afraid of this deadly gas and refused to consider the proposal which I put before him. He solved the problem by building walls at intervals along the culvert and packing all the cables with asbestos so that there could not be any flue effect if a fire occurred, and all such fires could be isolated.

The author insists on the value of rubble as a fire precaution, and I should like to say that in all our new works on the Belfast system we have made arrangements for any leakage of oil to drain away through rubble or gravel. Certain of our substations give us cause for concern from the fire-risk point of view, and we are quite willing to spend money on bringing them up to date, but sometimes we meet with opposition from our consumers. We keep before us above all the importance of continuity of supply.

Mr. F. W. Parkinson: The author favours the use of steel beams in building construction. While steel is clearly necessary for central-station construction, for substations reinforced concrete is surely preferable. A reinforced-concrete building is as nearly fireproof as possible, whereas steel beams are a source of weakness.

Mr. F. Johnston: I should like to know why the author is so severe in his criticism of aluminium, seeing that both aluminium and iron would be likely to melt in an oil flame.

He refers to a $\frac{3}{4}$-in. layer of sprayed asbestos. How is this material sprayed on?

I should also like to know something more about the Doble system of testing. Most fires are caused by breakdown of insulation, and the difficulty has been in making insulation tests not from one or other side of the installation to earth but from pole to pole. Does the Doble system take this into account, and does it enable one to measure the insulation resistance between poles without shutting down the system?

Mr. E. N. Cunliffe: It would appear that for the purposes of the paper a major electrical station is one which controls both legs of a duplicate feed to any town or district to which there is no other adequate means of supply. In the event, therefore, of the destruction of the station by fire, explosion, or bombing, there would be a total shutdown of supplies to the district for a period too long to be contemplated. I should be interested to know whether this description approximates to the author's own definition of a major electrical station.

There can be no doubt that for stations of this type the maximum precautions against fire should be adopted. In many cases it would be an advantage if duplicate transformer substations were split completely into halves, interconnected by cabling, and situated a few hundred feet apart, thereby feeding the lower-voltage network at two distinct and separate points. Such an arrangement should be completely immune from all possible risks, and I do not think the cost would be very much greater than that of the ordinary arrangement. The two small sites required might even be easier to find than a single site of the usual large dimensions.

Here in Belfast the majority of the recommendations put forward by the author are rapidly being put into effect. In all new substations from the largest step-down type to the smallest distribution type it has for some time past been standard practice to accommodate the switchgear and transformers in separate fireproof compartments, in each of which oil-drainage sumps of adequate capacity are formed. Special attention has been paid to substations on consumers' premises where the spread of an oil fire from the substation to the main buildings might involve disastrous losses, and every practicable precaution has been adopted in an attempt to make these substations safe. In the older type of rotary-convertor substation, however, the problem is more difficult as the plant does not always lend itself to ready subdivision. In such cases the transformers are being surrounded by dwarf brick walls, and oil-drainage pebble beds are being formed in cable trenches and other necessary places.

I agree with the author that fires in cable chambers are very rare. It is, however, possible for such fires to occur, and in this connection I would draw attention to a combination of circumstances which once nearly led to a disastrous fire. A 3-phase short-circuit occurred at the end of a long length of h.t. cable which was supported on cleats along the cable chambers and the walls of the station. The section of the cable was small, and the available fault power heavy; the switch failed to open, with the result that the cable was completely destroyed and set on fire at numerous points along the route, even though the circuit was finally cleared elsewhere after 2–3 sec. This shows that in stations of large capacity the cross-section of all h.t. cables should be made comparatively large, even if the cable is only intended for light duty. I should be interested to know whether the author is in favour of providing any form of automatic fire-extinguishing equipment for cable chambers or for cables racked in groups along station walls.

Apparently the majority of switchgear fires are accompanied by explosions of a violent nature which sometimes damage or destroy the building. This leads to the question of how far it is safe to subdivide the smaller switch-rooms into still smaller compartments, since by this means the "air-cushioning" effect is being decreased with consequent risk of building collapse. I should like to have the benefit of the author's experience in this respect.

Mr. J. A. C. King: I should like to ask the author to explain more fully his particular method of extinguishing an oil fire. I understand that he favours draining the oil into pits; is there not a danger of the water falling into the rubble-filled pit and floating out the oil, thus adding fuel to the fire from below as well as from above?

I read of a case recently where a large supply of oil, presumably from an oil tank, broke loose during a fire and found its most reasonable outlet in following the course of a river through a large town. The oil caught fire and turned the river into a sea of flame. A reinforced-concrete bridge was literally pulverized by the heat. Is there not a similar risk of serious damage where concrete is present in a substation?

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DISCUSSION ON

"THE USE OF PROTECTIVE MULTIPLE EARTHING AND EARTH-LEAKAGE CIRCUIT-BREAKERS IN RURAL AREAS"*

NORTH MIDLAND CENTRE, AT LEEDS, 26TH OCTOBER, 1937

Mr. W. T. J. Atkins: Regarding the "substation type" earth-leakage circuit-breaker illustrated in Fig. 5, I gather that this device has a field of application both with the system of individual earth-leakage breakers and also in connection with the system of multiple earthing of the neutral, although these two schemes are clearly distinguished and described as alternatives. I am rather concerned with the question of the discrimination of that leakage device as compared with the operation of the individual leakage-to-earth trips at consumers' premises. It is stated in the paper that discrimination exists, and no doubt this means current discrimination; but it seems to me that time discrimination is more important. Further, the substation earth-leakage trip is likely to invite trouble by functioning unnecessarily through lightning and other transient disturbances unless means are adopted to delay its action—by a mechanical time-lag or otherwise.

It is interesting to notice that about 0·5 VA is required to operate the trip coil of one of the domestic-type breakers. This represents a very good performance. I should like to know whether the coil is operated directly by alternating current or whether any form of metal rectifier is used in connection with it to improve the response. It should be possible to obtain more sensitive operation by such means.

In view of the large number of pitfalls which it points out, the paper rather gives support to the movement towards the use of appliances with insulating frameworks.

Mr. Douglas C. Field: The problem of obtaining low earth resistances in rural districts is well known, but the dangers inherent in this state of affairs have probably not been brought prominently to our notice owing to the fact that the large majority of rural wiring installations are fairly modern. The position will be different in, say, 10 or 20 years' time, when the installations and equipment have deteriorated.

I cannot help detecting in the paper one or two instances of bias in favour of multiple earthing; for instance, when considering earth-leakage circuit-breakers the author quotes 30 volts as a permissible maximum, whereas when discussing multiple earthing he mentions 152 volts as being safe.

When considering the specification of earth-leakage breakers he uses the terms "impedance" and "resistance" somewhat indiscriminately; when the electrode resistance is high the resistance only of the trip coil is of account, but when the series resistance is low the reactance must also be taken into consideration. When drawing up a specification there is no need to consider the tripping current and the coil impedance; it is only necessary to state that the leakage breaker shall operate with the application of, say, 30 volts across the trip coil and a resistance of 1 000 ohms in series with it.

On page 766 the author notes a number of disadvantages of earth-leakage circuit-breakers, and I shall deal with these in turn:—

(i) Lighting circuits should be on the "all-insulated" system, and so also should heating points in all rooms where no earthed metal already exists. This would ensure that the minimum of apparatus would be disconnected in the event of a leakage breaker operating.

(ii) The test key is provided to test the operation of the breaker only, but, as the author mentions, the very fact of there being a leakage trip enables the continuity of the earth wire to be tested quite simply.

(iii) If it is true that the breaker does not prevent its own metal case becoming alive, the solution is to have all-insulated covers, and I believe several makers offer these.

(iv) The low insulation resistance of heating-plates may be a drawback, but it would be interesting to know to what extent trouble has been experienced in this connection. In any event, it would seem to be a deficiency which cooker designers should overcome.

(v) When the amount of current which would pass through the human body is under consideration, why is the resistance of the body compared with the resistance of the trip coil and earth electrode? Does not the human body have a resistance to earth similar to that of the electrode? If the breaker will trip at 30 volts, dangerous conditions should not arise.

The author refers to the possible damage to apparatus on 3-wire or 4-wire systems should the neutral conductor break. I would point out that in such circumstances it is only apparatus which will be damaged, whereas in the case of multiple earthing a broken neutral conductor introduces a risk to human life.

In his "Conclusions on the Practical Tests" (page 777) the author refers to an increase in the voltage-drop in the phase wire when multiple earthing is used. I should be glad if he could explain the reason for this.

I am in agreement with the "Recommendations" (page 778), and especially welcome the last one. Forms of protection are our second line of defence; the first is insulation of the apparatus and installation. Although it is right that we should consider improving the system of protection, this should not lead us to neglect seeking improvement in insulation and the elimination of all appliances of inferior design and construction. On the

* Paper by Mr. H. G. Taylor (see vol. 81, p. 761).

whole I feel that in view of the proposed restrictions on the use of multiple earthing the evidence is in favour of the use of earth-leakage circuit-breakers.

Mr. T. D. Martin (Associate Member): The resistance of earth electrodes at consumers' premises shown in Fig. 1 seems alarming, and it would be interesting to know whether many undertakings test the earthing of rural schemes, especially when using "ordinary" earthing. A double-pole switch is shown in Fig. 7, but a single-pole switch would appear desirable, especially as a link is shown in the neutral; and it should not be necessary to run the earth-continuity connector to the incoming side of the main switch. The method suggested by the author (for ordinary earthing) of using the interconnected earth wire for a group of houses, and using the best earth connection available, is useful but may introduce complications where a number of contractors are involved in the work of wiring the property.

In one scheme in which protective multiple earthing has been applied the electricity undertaking took over the responsibility of providing the earth electrodes, and in this way ensured the efficiency of the earthing. The scheme is supplied by a 6·6-kV overhead line, with pole transformers at various load centres. In the majority of cases no town water main was available for earthing, the ground was fairly rocky, and high-resistance earths were anticipated, although it was expected that the earth resistance would be reduced on account of the plentiful rainfall in the district. The relative advantages of "ordinary" earthing and protective multiple earthing were considered, and it was decided to apply for permission to adopt the latter. All contractors in the area were notified of this decision. Single-pole switches were used throughout, and installation inspectors carefully checked the polarity. Polarized plugs were used for power circuits.

An additional advantage of a multiple earthing system is that it can easily be converted to "ordinary" earthing where this is found preferable, or if the change is requested by the Electricity Commissioners. I should like to ask the author whether he knows of any reason why a mixed system should not be used.

On domestic power circuits, the smallest wire allowed is 7/·029" and we have had no difficulty in blowing fuses of the requisite size for various installations. In fact, in one case where a jointer made a mistake in the polarity when connecting up a service, a 50-ampere fuse was blown on the l.t. side of the pole transformer.

At transformer positions the earth electrodes are in the form of cast-iron earth plates 18 in. square and ½ in. thick, and at consumers' premises they are either fluted hard-drawn copper rods or 1-in. wrought-iron tubes 6 ft. long with a screwed cap on top and fitted with a clamping screw to take the earth wire. Service cables are of either 0·04 sq. in. or 0·0225 sq. in. In some cases, transformers are placed on the ground and connected on both h.t. and l.t. sides by underground cables to the terminal poles. Transformers are of the outdoor type with cable-end boxes fitted, and it seems impossible to separate the earthing of the h.t. and l.t. sides owing to the transformer tank acting as a conductor between the leads of the h.t. and l.t. cables. I should like to ask the author whether he has come across this condition, and how it could be remedied. The resistance from the neutral conductor to the local town water main was checked at one place, and found to be about 0·5 ohm. Tests were made after a period of exceptional drought.

In selecting single-pole switch-fuses, care had to be taken that these were not of the 2-pole type converted by simply withdrawing one fuse bridge and placing a link across it, as it is possible to alter this type back and place the fuse in the neutral. Specially-constructed single-pole switch-fuses should be insisted upon.

When the merits of earth-leakage circuit-breakers and protective multiple earthing were being compared, some sample earth-leakage breakers were obtained and examined. In one sample it was possible for the push-button to stick in the intermediate position, disconnecting the installation from earth. We had also to bear in mind the doubtful condition of an earth-leakage breaker which has not been recently tested. The only disadvantage of protective multiple earthing is the danger arising from a broken neutral conductor, and dangers similar to this have existed since the early days of 3-wire d.c. distribution. It was therefore decided to proceed on the lines of protective multiple earthing.

In considering Table 3, the author points out that the neutral voltage-drop expressed as a percentage of the total line voltage-drop is less with multiple earthing than with single-point earthing, but he also states that the voltage-drop on the phase wire must increase with multiple earthing. I should be pleased if he could enlighten me on this apparent evasion of Ohm's law.

Mr. D. P. Sayers: My experience of rural installations is based on the system in Ireland with which I was concerned for some years. We decided to put in good earthing installations, and installed transformer earth-plates 3 ft. square, made of cast iron ½ in. thick, and buried 6 ft. deep. When we started testing these plates we found that earth resistances under 5 ohms were extremely rare and in some cases the value was 200 ohms or more; we had to be content with an average of 15 to 20 ohms. After a good deal of experimenting we found that the only way of getting a low earth resistance was by burying considerable lengths of old copper wire. In some cases hundreds of yards of wire were required to get down to a value of 1 or 2 ohms, particularly in sandy or rocky soil. The question of earthing of consumers' installations then came very much to the fore, as practically all the cookers had been supplied on the assisted wiring scheme and the undertaker was responsible for the complete installation. We found it extremely difficult to secure satisfactory earths. The small copper-tube electrodes of the kind commonly used for wireless sets gave very poor results, the resistance often amounting to hundreds of ohms.

In a certain village scheme which had just been completed, as soon as the transformer was switched on someone came rushing up and said a man working his pump handle had received a bad shock. The case seemed a mysterious one at first as the fuse of the service in question had not been put in and there was, apparently, no connection. Investigations revealed a double fault: firstly, a linesman had crossed the lead-in wires thus making the installation "alive" through the neutral link; and, secondly, there was a fault on one of the cooker elements. The cooker had been earthed to a pump,

which was found to have a high resistance, so that a person standing on the damp stone floor felt a shock when touching the pump handle. This combination of faults illustrates the risks that may be present in such installations.

Referring to Fig. 3, I would ask whether, if the side of the trip coil shown connected to earth could be connected instead to the neutral, the sensitivity of the arrangement would not be increased. Would not this change also eliminate the variation in sensitivity which is shown in Table 1 to obtain under certain conditions?

Finally, I would ask the author whether there has been any evidence of interference with radio reception on systems having protective multiple earthing.

Mr. K. C. Coop: I agree with Mr. Field in considering the author to be somewhat biased in favour of protective multiple earthing.

Referring to Fig. 10, he consoles himself with the fact that with an earth resistance of even 1 000 ohms there will only be a rise of 120 volts on the framework of apparatus when a 60-watt lamp is switched on. But it is also true that with an earth resistance of 10 ohms there will be a voltage-rise of 60 volts when 1 kW is switched on, and it is pointed out earlier in the paper that the E.R.A. considers that 30 volts must be regarded as a dangerous voltage. It is small consolation to know that the voltage-rise due to a 60-watt lamp under favourable conditions may be small, when a load of 6 kW is by no means uncommon on a domestic installation.

As compared with an all-insulated system there is the difficulty with protective multiple earthing of the use throughout of 3-pin plugs and sockets and 3-core flexibles on apparatus. The question is, how are we to insist on the standardization of 3-core flexibles when consumers are free to obtain their apparatus from multiple stores? Are the supply authorities to be responsible for all pieces of apparatus which consumers install?

Mr. I. Town: I agree with the author that the protection afforded to apparatus connected to a supply may be unsatisfactory when the installation is earthed to a small water supply or pump, or by plate or rod electrodes.

In Section (7), under "Recommendations," the author suggests "That greater attention be given, in the construction of all electrical appliances, to the provision of a higher standard of insulation." Such a recommendation is particularly applicable to the electric cooker on a rural supply where no efficient water mains are in existence, and where every consumer is a potential user.

There is no apparatus of general use which is so prone to leakage as the electric cooker, and it seems that the insulation resistance of most cookers is very low indeed after they have been in service from 6 to 12 months. Coupled with the low insulation resistance is a comparatively high fuse capacity, which calls for an earth of low resistance if the fuse is to be blown under fault conditions. I have experienced difficulty in obtaining a low-resistance earth by the methods outlined in Fig. 1.

Mr. B. D. Youatt: The G.P.O. has, I understand, been one of the chief objectors to the practice of multiple earthing, owing to the risk of interference with communication circuits. Since representatives of the G.P.O. have been associated with the author in conducting the tests described in the paper, it would be interesting to know whether any change in the official attitude may be expected.

Mr. J. G. Craven: I should like to ask whether the method referred to throughout the paper in connection with measurement of earth resistances complies with I.E.E. Wiring Regulation 1110, which gives interesting and full instructions regarding the testing of the effectiveness of an earth.

The question of broken neutrals is mentioned in the paper, and has been referred to by other speakers. I feel there need be no fears on this score, as breakages will only happen in practice in very exceptional cases, and it is impossible to legislate, by Regulations or otherwise, for the one chance of failure in a million.

I should like to know how the cost was met of the 700 earth-leakage circuit-breakers installed at Dumfries. If the supply authority paid for them, the effect must have been to keep the cost of energy up: and if the consumer, then each installation must have cost more.

It take it that the expression "true earth" should not be confused with "true neutral"; I gather that the "true neutral" on a system can and does move with the load on the network.

With regard to the question of animals coming into contact with "protective metalwork," does this term mean switchgear, conduits, and metal-sheathed cables which form part of farm installations?

It is suggested by the author that where protective multiple earthing is used a 6-ft. length of $\frac{3}{4}$-in. rod, or 1-in. pipe, should be driven into the ground as vertically as possible. I doubt whether in a great number of instances (e.g. in a farmyard, or outside a farmhouse) it would be possible to drive either of these into the ground to a depth of, say, 5 ft. 6 in.

The advisability is suggested of earthing the overhead neutral conductor of distributors on overhead lines four times per mile. Is this earthing to be done by means of an earth plate such as is used at the substation, or will some other and less costly method suffice?

I should be glad if the author would define "resistance area," and "true earth," and "earth continuity conductor." I do not think it is generally understood that the latter may take the form of the metal conduit or metal sheath of a cable.

[The author's reply to this discussion will be found on page 557.]

NORTH-EASTERN CENTRE, AT NEWCASTLE, 8TH NOVEMBER, 1937

Mr. N. S. Tennant: From my experience I would say that the values given in Table 1 for the resistance of consumers' earths in rural areas are typical of more than one network. In fact it appears that unless an extensive system of water mains is available or the system happens to be a metal-sheathed underground one, which is rarely the case in rural areas, the usual system of earthing is seldom safe. Even where there are water mains or a cable system exists it is desirable to make a test to ensure that the resistance is low enough to provide

safety, especially in the case of a fault occurring at a distance from the high-potential end of the apparatus. Care should be taken in making the connection to a water pipe, especially a lead one, as cases have occurred of a fault burning a hole in the pipe due to a loose connection. Earthing to the cable sheath in the case of an armoured network is usually satisfactory, but again a measurement should be made of the total earth resistance.

The author deals at some length with earth-leakage circuit-breakers. It appears from Fig. 4 that standardization of circuit-breakers is very desirable, and this Figure also brings out the important point that for a breaker of given characteristics there is a limit to the magnitude of the fault and earth resistances. I agree with the author that there should usually be no difficulty in obtaining fault and earth resistances of the order of 200 ohms; with a good trip coil such a value is satisfactory, although there are cases where even this figure would be difficult to obtain. Table 1 gives examples of the tripping voltages required in practice, which are distinctly alarming. The relation of earth resistance to tripping voltage given in this Table is variable, and I hope that such results are not typical. I would only say that it seems very desirable to make a test before passing any circuit-breaker installation as satisfactory. Earth-leakage circuit-breakers have been extensively used and appear to have been fairly satisfactory. The lack of discrimination where only one is installed has, however, proved a drawback, particularly in the case of isolated installations such as farms. The farmer may put up with disconnection of his appliances at night, but he much objects to his lights being put out of action, necessitating night calls for the service engineer.

Where animals are kept there seems no alternative to the use of the earth-leakage circuit-breaker. I understand that the E.R.A. has not given its blessing to neutral earthing in such cases, and that a recent consent of the Electricity Commissioners to multiple neutral earthing excludes the connection of the neutral to the framework in such circumstances. I should like to have some further remarks from the author as to what system he suggests in circumstances like these, as the isolated farm with its own special transformer is one of the commonest and most troublesome cases met with.

Protective multiple earthing is dealt with at length by the author, and the figures given in Table 3 show that with this type of earthing there is little to fear except under fuse-blowing conditions. Phase-to-neutral faults require immediate isolation, and on some networks without branch fuses a phase-to-neutral fault would not blow the fuses. Fuses complying with the British Standard Specification should be used rather than the usual porcelain-handle tubes, and branch fuses should be put in special places.

I know of only one instance of a broken neutral wire, but I have two cases in mind of a neutral link being left out. These were only revealed by the lamps burning out owing to high voltage. I have little doubt that other cases of this sort have occurred. The danger of a broken neutral wire is examined in Fig. 11; it would be interesting to know whether there are limits to the value of R_1W or R_2W. One would expect R_1 or R_2 to decrease with the number of consumers, and W to increase. Evidently if the value of RW exceeds 20 a dangerous condition exists, and I think the safety of consumers depends mainly on the assured continuity of a low-resistance neutral wire. The author refers (page 771) to a leakage circuit-breaker installed at the substation, and such a device seems desirable although the Electricity Supply Regulations do not mention it.

What is the least number of consumers to which the author would apply multiple earthing? Connected to most village networks there are a certain number of factories—such places as the creameries of the Milk Marketing Board, garages, etc.—and these come under the Factory Acts. Some of the motors installed are direct-coupled to machines, and although the declared voltage might not in itself be harmful a trifling shock might lead to an accident. Can the author tell us the views of the Home Office on multiple neutral earthing?

I approve the author's suggestion as to the conditions to be complied with when using multiple neutral earthing. It is evidently important to have the true earth-point of the system near the middle, as is the case with the ratio of resistances proposed by him. I notice that the Electricity Commissioners in a recent consent ask for the neutral point of the transformer to be bonded to the sheaths of any cables. If this requirement is complied with, a low earth-resistance may be expected at the transformer, and a ratio of 4 : 1 between any two resistances might be unobtainable.

Mr. E. Fawssett: Our company controls about 800 small networks, and we have never had an instance of a neutral conductor breaking alone. Certain companies abroad have had trouble of this sort, but I believe it has been due to somewhat inferior construction.

The results of the author's tests on earth-leakage circuit-breakers are frankly disturbing, but I think they were representative of the state of the art at the time the measurements were made. It must be borne in mind that earth-leakage circuit-breakers are delicate apparatus of rather flimsy construction; they are installed in situations where the mains voltage is present and where they are possibly liable to a certain amount of corrosion which will affect the tripping voltage. Unless these switches are well maintained they may put us in the position of living in something approaching a fool's paradise.

The co-operative spirit which exists in Dumfriesshire between the undertaking and the consumers enabled Mr. Pickles to get the consumers to install earth-leakage circuit-breakers at their own cost. If we were to adopt this solution, however, we should be faced with a considerable capital expenditure, as it is most improbable we could get our consumers to respond in the same way; but it is the maintenance much more than the capital outlay that has deterred our company so far from adopting these switches as a general solution.

As regards the conditions for installing protective multiple earthing, I feel that we can easily spend too much money in trying to get down to low earth-resistance values. I think it is more important to make sure that we have a thoroughly sound mechanical job for the return circuit, and with that a properly graded scheme of branch network fuses.

Mr. F. E. Heppenstall: On page 765 it is stated that the E.R.A. considers that the maximum potential which

should be tolerated permanently on metal frameworks is 30 volts. In some tests I made on myself with dry hands I could not feel 40 or 50 volts, but with wet hands I could feel 10, and at 15 volts I had to let go of the terminals. I should like to know how the E.R.A. arrived at the figure of 30 volts, as at this voltage people using wash-boilers and similar appliances might get a small but unpleasant shock.

It is evidently the author's intention that water mains should be used for earthing if they exist, but the low resistance of these should not be taken for granted. The I.E.E. Wiring Regulations require a maximum earth resistance on an installation of 1 ohm, a figure that can be justified from consideration of the maximum safe voltage on the appliance framework with faults which may occur at any point of an element or winding. This resistance is not easily measured where the earth connection is made to water pipes, but the total earth-circuit resistance is the more important and more easily measured figure. My company made a number of tests of the earth-circuit resistance in Newcastle, and of 74 readings the average was 1·15 ohms, with a minimum of 0·3 ohm and a maximum of 3·8 ohms. Earths to water pipes are therefore usually good, but not always so. Where water mains exist in rural areas these figures would probably be exceeded.

In the author's conditions for the adoption of multiple earthing the requirement of a maximum resistance of 10 ohms at 4 points per mile of line will probably be too difficult to comply with. An earth rod 6 ft. long by 1 in. diameter would have an earth resistance between 25 and 100 ohms, depending on the nature of the soil; so that in order to obtain a value of less than 10 ohms four or five of such rods in parallel might be required, and as they should be spaced about 15 ft. apart that condition might be somewhat difficult. It seems to me that if the figure of 10 ohms were exceeded, more dangerous conditions might arise (see Fig. 11, where the voltage on frameworks depends on RW).

Condition (iv) under the heading " Recommendations " on page 778 imposes too elaborate a test. I think a continuity test is advisable. Such a test as the author requires would be very long and expensive.

In considering the objections to the use of earth-leakage circuit-breakers, the author states that cooker boiling-plates when damp may have sufficient leakage to cause the trip to operate on switching on. A short time ago I made a number of tests on boiling-plates; although it was found that by damping with steam the insulation resistance could be considerably lowered—in one case to 10 000 ohms—there was not sufficient leakage current to operate the trip.

Mr. H. Leyburn: I propose to confine my remarks to a criticism of the author's " Recommendations " and " Proposed conditions which should be complied with where protective multiple earthing is used," given at the end of the paper. I shall also give proposals for simple rules which, in my opinion, are sufficient to deal with all urban and rural installations.

I agree in principle with Recommendation (i), namely that protective multiple earthing be permitted in rural areas subject to compliance with certain conditions. One of the main reasons that has led me to adopt this view is that this policy would enable installations in rural areas to be brought into line with those in urban areas so far as the wiring of the installation is concerned, it being understood, of course, that those in urban areas would rely for earthing on a water-main or cable-sheath.

I cannot, however, agree with Recommendation (ii), namely that farm installations where animals may come into contact with protective metalwork should be treated differently from house installations. It might be difficult in practice to draw a distinction between these two types of installations; further, if this recommendation were accepted, one of the essential conditions, namely standardization, would be lost.

Recommendation (iii), specifying that the total resistance in the earth circuit at any time of the year should be low enough to pass $2\frac{1}{2}$ times the current rating of the largest fuse, does not appear to be safe, because the resistance of the earth circuit of the type referred to in this recommendation is variable; and it would therefore be difficult, if not impossible, to ensure that the relation specified always held good. I suggest that it would be safer not to rely on small water systems such as are frequently found in farms, but to treat such an installation in the same way as one not associated with a water supply.

Incidentally, in connection with this point and with Recommendation (iv), I should like to know the method that the author would recommend for testing the total resistance of the earth circuit. A device called the Earthometer, described by me a few years ago, has been developed especially for the purpose of taking these measurements quickly and reliably. Its main components are an indicating meter calibrated in ohms, a small step-down transformer, a polarity-indicating lamp, testing leads, and a flexible cable with an adaptor capable of being plugged into a socket or lampholder. The outstanding feature of the Earthometer is that it measures the impedance of the complete earth-fault circuit from the framework of the apparatus under test right back to the neutral earth electrode of the supply substation. If the supply voltage to earth and the impedance of the complete earth-fault circuit are known, the magnitude of the current that will flow on the occurrence of an earth fault can be determined; and, by comparing this figure with the fusing current of the largest fuse of the installation, it can be ascertained whether the earthing is efficient or not.

Turning now to the " Proposed conditions which should be complied with where protective multiple earthing is used," I do not consider it essential that an earth electrode should be used on each consumer's premises, as specified in Condition (ii); in fact I would suggest that such earth electrodes can be safely omitted and that earth electrodes on the distributor only should be provided. These earth electrodes, being under the supervision of the supply authority, could be maintained more easily than electrodes on consumers' premises and would therefore be more conducive to safety.

In connection with the method of earthing the neutral, specified in Condition (iii), the author omits an important point, namely that in order to guard against a break in the neutral distributor, however remote this contingency may be, it is necessary to provide an earth electrode

having a very low resistance at a point most remote from the substation. The additional condition specified, namely that the ratio of the maximum to the minimum earth-electrode resistance should not exceed 4, is in my view unnecessary and uneconomical.

In connection with Condition (v), I consider that the earth-continuity conductor should not be connected to the neutral at the meter board but that it should be connected right back to the neutral distributor, so that in the event of a break of the neutral conductor between the meter board and the distributor there shall be no danger to the consumer.

I do not see the reason for the special condition specified in the latter part of (vii). If the installation is laid out and wired in the same way as any urban installation, there is no reason for any special tests to be applied for checking the current-carrying capacity of the neutral conductor.

Finally, there is one condition that I think should be included, namely that earth-leakage protection should be provided at the substation. I do not think that over-current protection as specified in Condition (ix) is sufficient, because in the event of a break of the neutral distributor the over-current relay may not operate, whereas an earth-leakage relay would do so. It may be that a biased earth-leakage relay, arranged to respond to fault current and not to unbalanced load current, may have to be used. Tests in this connection would be welcome.

Dealing with the problem of consumers' installations in its broadest aspect, I consider that one of the main aims always to be kept in view is standardization. Without it, the progress of the electrical industry is certain to be retarded. It is particularly important that the layout and wiring of installations should be standardized wherever possible, and with this aim in view I suggest that the following simple rules should be adhered to in all consumers' installations:—

(1) Where water mains or cable sheaths are available for earthing, i.e. mainly in urban districts, ordinary solid earthing should be applied.

(2) Where earth electrodes, as specified in (1) above, are not available but where multiple earthing of the neutral is deemed feasible by the supply authority, i.e. mainly in rural districts, the authority should provide on consumers' premises an earthing terminal connected to the multiple-earthed neutral for use as an earth electrode.

(3) Where neither earth electrodes as specified in (1) above are available, nor multiple earthing as in (2) above is deemed feasible, i.e. in rural districts with high-earth-resistivity, earth-leakage circuit-breakers should be used.

If rules somewhat on the above lines were adopted, the layout and wiring of installations, except possibly those in (3) above, would be standardized to the greatest possible extent; and if a rural area were changed into an urban area it would not be necessary to modify the installation in any way.

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LEEDS AND NEWCASTLE.

Mr. H. G. Taylor (*in reply*): A number of criticisms which have been levelled against protective multiple earthing in connection with this paper arise from the detailed consideration which has been given to the question of the voltages which occur on protective metalwork when a fracture of the neutral conductor takes place. The majority of this criticism could have been avoided if, in accordance with our view that the neutral conductor practically never breaks alone, we had neglected to consider the possibilities which arise in such an eventuality. Attention was given to the matter, however, in order to refute the incorrect statements which have been made in the past relating to the voltage-rise which can occur on the metalwork when the neutral is disconnected. We do not admit that this is anything but a very rare occurrence in this country; nevertheless it seemed worth while to point out that should it occur the conditions would not be as dangerous as has been stated.

Mr. Atkins raises the question of discrimination with substation-type earth-leakage circuit-breakers. This matter is dealt with in some detail on page 771 of the paper, and it is hardly necessary to make any further reference to the matter except to indicate that when a fault occurs on the consumer's premises the current which flows through the substation earth-leakage circuit-breaker is only a very small proportion of that which flows through the consumer's earth-leakage circuit-breaker, and consequently there is no question of the former ever operating prior to the latter. I am not aware of any case where a metal rectifier has been used in connection with earth-leakage circuit-breakers to improve their sensitivity, but this is a matter which might well be considered by the manufacturers.

In reply to Mr. Field, on the question of the safe maximum voltage-rise on apparatus, it is not stated in the paper that 152 volts is safe, and it was not intended to imply that this was the case. It is shown in the paper that in certain circumstances with protective multiple earthing when the neutral conductor breaks, such a voltage can occur on apparatus; but the object of stating this was to show that the value is considerably less than the line voltage, which has in the past been stated as the value which can occur on metalwork. This answers also the question raised by Mr. Coop.

The question of specifying the characteristics of earth-leakage circuit-breakers is now under consideration by the British Standards Institution. I agree with Mr. Field that the "all insulated" system should be used for earth-free installations; danger is created by introducing an earth where one does not already exist.

With reference to the low insulation-resistance of cooker boiling-plates, the E.R.A. has been informed of the difficulties which occur, but there is little evidence that they are widespread.

In connection with Disadvantage (v) to which Mr. Field refers, it is not correct for two reasons to assume that the human body has a resistance to earth similar to that of the electrode; one is that the individual may be standing in a locality or on a floor which has

a very different resistivity from that of the soil where the earth electrode is situated, and the other is that the resistance to earth is a function of the size of the electrode, and an adequate comparison can therefore only be made by comparing the size, depth of burial, and shape of the earth electrode, with the size of the man's feet, the type of footwear, and various other factors.

Mr. Martin and Mr. Field both raise the question of the voltage-drop in the phase wire when multiple earthing is used. This is not a resistance effect, but is due to the change of reactance which occurs when part of the current flows back through the earth instead of through the neutral wire. Clearly, in these circumstances the complete circuit is more reactive and the reactance drop of the phase wire is higher than when the total current returns through the neutral wire, which is in close proximity to the phase wire.

I am very glad to have Mr. Martin's account of his experience with a system of protective multiple earthing, and his evident satisfaction with the system is an encouragement to other engineers to make similar experiments. There is a very good reason why a mixed system of ordinary earthing and protective multiple earthing should not be used. This is that if a low-resistance fault occurs on the installation which uses ordinary earthing, the current flows through this fault and back to the neutral, via all the multiple earths in parallel. If the direct earth has a lower resistance than the multiple earths on the neutral, the proportion of the total voltage-drop over the multiple earths will be greater than that over the ordinary earth, and this may result in the neutral being at a dangerous voltage with respect to earth. If 30 volts is taken as the dangerous value, this means that separate earthing should not be used if the value of the direct earth resistance is less than 7 times the resistance of the whole neutral to earth.

I am grateful to Mr. Martin too for drawing attention to an earth-leakage circuit-breaker with a sticking push-button; this is the second instance of which I have heard, and is a matter which should be taken into account by the British Standards Institution in drafting their Specification.

In reply to Mr. Sayers, the disadvantage of connecting an earth-leakage circuit-breaker to the neutral is that in the event of a phase-to-neutral fault at one installation the neutral may momentarily be raised to a sufficient potential with respect to true earth to operate all the neighbouring earth-leakage circuit-breakers.

In reply to Mr. Youatt, I am afraid that I cannot speak on behalf of the G.P.O., but I can say that I understand that they are prepared to accede to requests for protective multiple earthing which are made through the Electricity Commissioners, and that in the event of any special circumstances arising their attitude would not be an unreasonable one.

In reply to Mr. Craven, the measurements of earth resistance described in the paper were carried out in accordance with Regulation 1110 in the Tenth Edition of the I.E.E. Regulations for the Electrical Equipment of Buildings.

As explained by Mr. Fawssett, the cost of the earth-leakage circuit-breakers in the Dumfries area was met by the consumers. There was no intention to distinguish between "true earth" and "true neutral" except in so far as the latter is a point on the neutral conductor which is at no difference of potential from the general mass of earth. This point does move about on the neutral as the load varies.

"Protective metalwork on farms" refers to the switchgear, conduits, and metal-sheathed cables. The type of earthing required on the distribution system will depend on the resistivity of the soil, and may consist of plates, pipes, or strip or conductor earth-electrodes. Probably the last-mentioned is the cheapest form; it is constructed by burying lengths of spare or scrap copper conductor in the ground at 1 ft. to 1 ft. 6 in. below the surface. The conductor should be buried in straight lines, and it is often advantageous and convenient to place it at the bottom of a ditch, where the soil is moist.

"Resistance area" as applied to an earth electrode, and "earth-continuity conductor," are defined in the I.E.E. Wiring Regulations. The expression "true earth," used when one wishes to define the potential of the electrode or conductor, refers to that point in the ground which is so far removed from an earth electrode that its potential is the same, for all practical purposes, as that at any more distant point. In fact, "true earth" is any point in the ground outside the resistance area of an earth electrode.

I am glad to have Mr. Tennant's comments, and agree with his suggestion that it is desirable to make a test before passing an earth-leakage circuit-breaker installation. With reference to farm installations, I understand that the recommendations of the Electricity Commissioners are that protective multiple earthing shall not be used at farms if animals may make contact with the protective metalwork. It seems, therefore, that it may be used provided the metalwork is kept out of reach of the animals. This matter is, however, receiving further consideration by the E.R.A., and will be dealt with in a Supplementary Report, as will also the question of the resistance values of the earth electrodes required for the distribution system.

I do not see any reason why there should be a minimum number of consumers for which protective multiple earthing should be used. I cannot speak for the Home Office, but my impression is that they are prepared to give favourable consideration to applications for protective multiple earthing, provided that it is carried out in a satisfactory manner.

Mr. Fawssett thinks it most improbable that consumers in his area would be prepared to meet the cost of earth-leakage circuit-breakers. In this connection it is of some value to note that in Australia, where a large change-over to earth-leakage circuit-breakers is taking place, the undertakings are themselves meeting the cost of installing one earth-leakage circuit-breaker in each installation. Additional circuit-breakers or replacements must be provided by the consumer.

Mr. Heppenstall's self-applied shock tests are very interesting, and the difficulty which he felt in holding electrodes with wet hands when the difference of potential was 15 volts suggests that the E.R.A. figure of 30 volts is not abnormally high. The criticism which has generally been experienced is that the value is too low.

It will be appreciated that some figure had to be arrived at which was not so high that fatal shocks could readily be obtained, but on the other hand was not so low as to make it impossible for protective systems to comply. Later information has shown these data to be unreliable. I am not aware of any previous tests which have been made to determine the earth resistance of a large number of installations using the water pipes as earth electrodes, and the information on this subject which Mr. Heppenstall gives is very valuable.

The insulation resistance of boiling-plates varies very considerably, and I understand that there is a marked difference between two classes of plate which use different insulating materials.

I am interested to have Mr. Leyburn's extensive comments on the recommendations of the paper, and am pleased to be able to inform him that the question of farm installations is receiving further consideration by the Electrical Research Association and that the matter will be dealt with in the Supplementary Report to which I have already referred.

There is some difference between what Mr. Leyburn refers to as the "total resistance of the earth circuit" and the circuit which it is intended should be measured before protective multiple earthing is used. The intention is that the resistance of the earth-continuity conductor should be measured, but that these tests should be carried out with an appreciable current. The Earthometer which he describes is a very useful instrument for measuring the resistance of the neutral lead together with the two earth electrodes, but with protective multiple earthing it is not essential to measure the whole circuit.

I agree that it is not essential to use an earth electrode at each consumer's premises, but only on the condition that the earth-continuity conductor is run right back to the neutral distributor. Unless this is done the consumer is exposed to greater danger when his neutral service wire is broken than he would be if an earth electrode existed on his premises.

Mr. Leyburn does not state how low the earth resistance should be at the end of the neutral distributor, and he does not point out that every time the distributor is extended (which often occurs in rural areas) it would be necessary to install another low-resistance electrode. In my opinion it is better to prescribe that there should be so many electrodes per route mile of the installation, and to attempt to limit their resistance to some value which there is reasonable hope of the undertaking being able to obtain; and for those consumers who are at the end of the distributor beyond the last low-resistance earth electrode, reliance must be placed on their own earth electrodes.

It is agreed that in any system using ordinary earthing the earth-continuity conductor should be in as satisfactory a condition as when protective multiple earthing is used; but it cannot be denied that in many existing installations if the earth electrode had a really low resistance the earth-continuity conductor would be unable to carry the fault current. With a protective-multiple-earthing system the fault current must of necessity be large, and it is therefore very desirable that the earth-continuity conductor should be adequate to carry it. Possibly a similar test should be made in systems using a satisfactory form of ordinary earthing.

DISCUSSION ON "THE EXAMINATION AND RECORDING OF THE HUMAN ELECTROCARDIOGRAM BY MEANS OF THE CATHODE-RAY OSCILLOGRAPH"*

NORTH MIDLAND CENTRE, AT LEEDS, 7TH DECEMBER, 1937

Dr. S. J. Hartfall: All our electrocardiographic work in hospital is at present done with the string galvanometer, and if the results reproduced in the paper are average samples of work done with the author's instrument then an enormous advance has been made. I should like to know whether the apparatus is cheap and portable. Can it be brought to the bedside of the patient, and what would be the cost to our hospitals if we advised them to buy it?

Mr. R. M. Longman: The paper describes the combination of a high degree of amplification (such as is obtained in wireless work) with the cathode-ray oscillograph, and its application to the study and alleviation of suffering. There can be little doubt of the improvement the author's instrument makes on the Einthoven galvanometer, which has been invaluable for the last 30 years.

I should like to know the effect of a reduplication of the heart beat, which, however, disappears after heavy exercise. I should also be interested to know the effect on the heart beat of physical or mental shock.

Mr. J. G. Craven: In the Summary the author speaks of the cathode-ray oscillograph as being devoid of inertia. Is this strictly true? An engineer, either electrical or mechanical, finds it difficult to imagine anything which moves but is devoid of inertia.

* Paper by Dr. D. Robertson (see vol. 81, p. 497).

In the author's demonstration, when the patient was coupled to the cathode-ray oscillograph and was asked to clench his fist the record obtained seemed to be made up of the 5th, 9th, 13th, and all the rest of the harmonics. It was quite a good example of what we do not want in alternating-current machinery, and showed the difficulties the author has been up against in his research work.

I learn that the small voltages which are recorded on the electrocardiograph are not induced in any way, but are due to more or less the same type of action as occurs in an ordinary cell, i.e. chemical action. It is amazing to think that these minute voltages which exist in the body are recordable by the author's apparatus.

Dr. Douglas Robertson (*in reply*): I can assure Dr. Hartfall that the specimen electrocardiograms (Fig. 21) illustrating the paper, and also those shown during the meeting, are a fair average of those which I get with the apparatus in its present form. As mentioned in Section (8) of the paper, a little care is necessary in exposure and development if a good clean curve is to be obtained.

Arising directly out of Dr. Hartfall's remarks I should like to stress a point which I am convinced is of great importance in obtaining good clean electrocardiograms; and it is a point to which I feel not enough attention is paid in routine electrocardiography. I refer to the avoidance of all possible extrinsic muscular action, the action potentials of which will necessarily obscure the finer details of the electrocardiogram and upset the clean appearance of the curve. This is especially important with the cathode-ray electrocardiograph, since its high-frequency response is appreciably better than that of most other electrocardiographs; and it is also a desirable procedure with other types of electrocardiograph if really clean curves are to be obtained. It is essential for the patient to be really relaxed, so that not even involuntary muscle tremor or tonic muscle action, of sufficient degree to produce appreciable action potentials, is present. To this end he must be comfortably seated in an arm-chair with his arms supported. If he is in bed, extra pillows to act as arm-rests may be found helpful. And a few moments spent in reassuring him (and especially her) about this, to him, strange examination will be tenfold repaid in the clean curve that results.

The apparatus is completely portable, and was in fact specially designed so that it allows immediate and easy examination of the electrocardiogram at any bedside. It is for this reason also that considerable pains have been taken over the question of obtaining the high voltage necessary for the cathode-ray-oscillograph from the supply mains, since high-tension batteries to give the requisite 800 volts will necessarily be so heavy as to render the apparatus much less portable. At present the cost of the apparatus is slightly less than that of most other types of electrocardiograph.

In reply to Mr. Longman, I would refer him to "Heart Disease" by Dr. Paul White, and to my answer to Mr. Strafford's question in the London discussion.

I apologize to Mr. Craven for my rather loose statement with regard to the absence of inertia in the cathode-ray oscillograph. Nevertheless, as the cathode ray is a stream, or jet, of electrons the mass involved is (I speak in all humility as no physicist) only that of the electron, namely 9×10^{-28} gramme. So that, even if it is moving at high velocity, the inertia present must be very small. Let us say, therefore, that "for all practical purposes" the cathode ray is without inertia. After all, it follows fairly accurately the vagaries of the B.B.C. television studio for a picture 12 in. wide, containing, in effect, 405 lines and changing 25 times every second. I think, therefore, we may say, speaking mathematically, that the inertia present in the cathode ray as the moving part of a measuring instrument—the cathode-ray oscillograph—at least approaches zero. I do not pretend that the electrocardiograph described is free from inertia; but what inertia there is is artificially introduced in the filter-circuit units [see Sections (5) and especially (7) of the paper], and is directly under the control of the experimenter; it is *not* in the cathode-ray oscillograph. With other types of electrocardiograph where the moving part has appreciable mass such control is obviously impossible.

In conclusion, I should like to mention one reference which was omitted from the list at the end of the paper and which would have been included had it come to my notice earlier. It records the use of the cathode-ray oscillograph for electrocardiographic purposes as early as 1927 and is of historical interest only:—

Dock, W.: "The use of the Cathode-Ray Oscillograph for Electrocardiography," *Proceedings of the Society for Experimental Biology and Medicine*, 1926–7, vol. 24, p. 566.

DISCUSSION ON
"THEORY AND PERFORMANCE OF THE ICONOSCOPE"*

Dr. F. C. Williams (*communicated*): The sections of this paper of greatest interest to me are those dealing with the signal/noise ratio. The exact calculation of noise in such a complicated device is a matter of considerable difficulty, and the authors appear to have made some simplification in the earlier section entitled " Calculation of the sensitivity of the iconoscope." Here they calculate the noise output with reference only to the thermal noise in the coupling resistor and shot noise in the amplifier; they omit the shot noise originating in the iconoscope.

They state on page 109 that "$\overline{V}_N^2 = K_2 f R$, where K_2 is the shot coefficient," but they appear to refer to K_1, the thermal coefficient defined earlier on that page. The present discussion assumes that such is the case.†

Although the beam current does not in fact traverse the resistance R, it appears probable that its shot fluctuations will generate a noise across R relevant to such traversal. Further, the secondary and photo-currents which make up the actual return path of the beam current will probably contribute a further, more or less independent, shot fluctuation across R. Thus if I_b is the beam current, it appears very probable that there will be a fluctuation current traversing R whose mean-square value is

$$\overline{i}^2 = 2A_b I_b e d f$$

where A_b is some factor, probably not less than 2, which expresses the extent to which the fluctuations in R exceed those relevant to the passage of a temperature-limited current I_b through R. That A_b will be of the order of 2 seems to be implied in the section relating to electron multipliers; experimental evidence of its probability can be derived from the known properties of tetrode valves. With many such there exists an equilibrium potential for the anode (otherwise than zero) for which the anode current is zero. If the valve be set to operate at this point (by momentarily raising the anode potential above that of the screen) with a condenser and resistance in series connecting the anode and cathode, conditions are closely analogous to those obtaining in the iconoscope. Mr. E. B. Moullin has examined the fluctuations generated in R under such circumstances.‡ He found A_b to be of the order of 2 or more; precise statement is impossible since I_b was unknown and flicker effect was present.

It follows that the signal/noise ratio in the iconoscope is the same as that obtaining in a simple photocell and amplifier having a photo-current $A_b I_b$, the signal photo-current being given an arbitrary r.m.s. value I_0 for the time being. I have discussed this last circuit in a paper recently submitted to The Institution.† It is there shown that with the circuit of Fig. A the (noise/signal)² ratio is

$$S^2 = \frac{2A_b I_b e f_0}{I_0^2}\left\{1 + \frac{2kT}{eRA_bI_b} + \frac{AI}{g^2A_bI_b}\left(\frac{1+\frac{1}{3}R^2C^2\omega_0^2}{R^2}\right)\right\}$$

where

A_bI_b = mean photo-current.
I_0 = r.m.s. signal current from the photocell.
R = coupling resistance in series with the photocell.
C = interelectrode and stray capacitance from grid to earth.
I = mean anode current of the valve.
A = measure of the depression of shot effect by space charge.
g = mutual conductance of the valve.
$f_0 = \omega_0/2\pi$ = band width to which the amplifier responds;

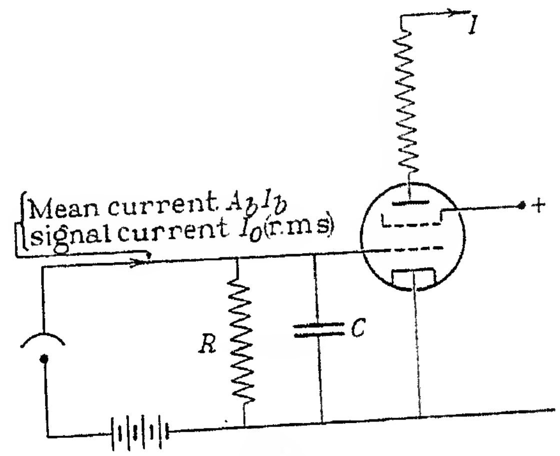

Fig. A

it is assumed that by means of correcting circuits later in the amplifier the response is held constant at all frequencies from zero to f_0 whatever the value of R, and that the response is zero above f_0.

It is evident that, as R is increased, S decreases steadily to the limit

$$S^2 = \frac{2A_b I_b e f_0}{I_0^2}\left\{1 + \frac{AIC^2\omega_0^2}{3g^2A_bI_b}\right\}$$

thermal noise in R, represented by the second term in the first expression, being then negligible. The term outside the bracket is the (noise/signal)² in the photo-current, or, in the case of the iconoscope, the basic limit at the mosaic. The second term inside the bracket represents the fractional extent to which valve noise supplements the basic noise. Valve noise will be negligible if

$$\frac{AIC^2\omega_0^2}{3g^2A_bI_b} < 1$$

* Paper by V. K. Zworykin, Ph.D., G. A. Morton, Ph.D., and L. E. Flory (see page 105).
† The authors have confirmed that the correction should be made.
‡ *Proceedings of the Royal Society*, 1934, A, vol. 147, p. 100. Actually the condenser was short-circuited in his experiments. Since I is zero this is immaterial; the fluctuation in R will be unaffected by its introduction, provided it is great compared with the anode-cathode capacitance.

† "Co-existent Thermal and Thermionic Fluctuations in Complex Networks."

i.e. $$I_b > \frac{AIC^2\omega_0^2}{3g^2A_b}$$

With typical values this reduces to

$$I_b > 0 \cdot 15\ \mu\mathrm{A}.$$

Hence with a high value of coupling resistance ($R = 10^5$ to 10^6 ohms is sufficient) and subsequent frequency compensation, we shall have, if $I_b = 0 \cdot 5\ \mu$A,

$$S^2 \simeq \frac{2A_bI_bef_0}{I_0^2}$$

With the authors' notation, and with $I_0 = FpkA$, this reduces to

$$\frac{1}{N} = S = \frac{\sqrt{(2A_bI_bef_0)}}{FpkA}$$

or $$F = \frac{N\sqrt{(2A_bI_bef_0)}}{pkA}$$

Hence with $N = 10$, $A_b = 2$, and $I_b = 0 \cdot 5\ \mu$A, and their values for the remaining factors,

$$F = 0 \cdot 2 \times 10^{-3}\ \mathrm{lumen/cm^2}$$

as against $0 \cdot 7 \times 10^{-3}$ lumen/cm² according to the authors.

Thus the use of high R and subsequent correction should improve the sensitivity by a factor of $3\frac{1}{2}$.

The improvement obtained by this method does not appear capable of attaining such values as are possible with secondary multiplication, for valves are not available for which $\frac{AIC^2\omega_0^2}{g^2Ab}$ is sufficiently low to permit of the advantageous use of much lower values of I_b. But it does appear that the adoption of the system would permit of the more advantageous use of the present commercially-produced iconoscopes.

It is perhaps worth noting that it can be shown from the first equation that the authors' assessment of valve noise is probably rather high; if the same typical valve properties are assumed for $R = 10^4\omega$ as were assumed for high values of R, the value of F is about $0 \cdot 5$ lumen/cm²

INSTITUTION NOTES

JOINT COMMITTEE ON MATERIALS AND THEIR TESTING

The Joint Committee on Materials and their Testing, consisting of representatives of some 25 technical Institutions and Societies (including the I.E.E.), which was formed in 1937 to act as the British national organization in matters relating to materials and their testing, has now issued an Annual Report on the work of the Committee for the year ended 28th March, 1938. Copies of this Report can be obtained by members of the I.E.E. on application to the Secretary of the Joint Committee at The Institution of Mechanical Engineers, Storey's Gate, London, S.W.1.

INTERNATIONAL ENGINEERING CONGRESS, GLASGOW, 1938

Members are reminded that the International Engineering Congress, full details of which were enclosed with the March issue of the *Journal*, will take place in Glasgow from the 21st to the 24th June. Applications to participate in the Congress should be made on the requisite form, also issued with the March issue of the *Journal*, and should be forwarded to the Hon. General Secretary of the Congress, Mr. P. W. Thomas, 39 Elmbank Crescent, Glasgow, C.2.

The closing date for the receipt of applications will be the 31st May.

METER AND INSTRUMENT SECTION MEETING, 20TH MAY

Owing to unforeseen circumstances Prof. G. Keinath, who was to have given a lecture at the above meeting on "New Measurement Technique, with particular reference to Alternating-Current Measurement," will not be able to be in England at that time. The following lecture will therefore be substituted: "Electrical Temperature Measurements in Physiology," by Prof. A. V. Hill, O.B.E., Sc.D., F.R.S.

GRADUATESHIP EXAMINATION RESULTS: NOVEMBER, 1937 (SUPPLEMENTARY LIST)*

Passed†

Alexander, Nellumatil Thomas (*Ceylon*).
Balkrishnan, Narayana Iyer (*India*).
Bhatia, Manmohan Singh (*India*).
Chatterjee, Amiya Kumar (*India*).
Curtis, Donald Cuthbert (*New Zealand*).
Dastur, Naval Jamshedji (*India*).
Deshpande, Dattatraya (*India*).
Deshpande, Murlidhar Vinayak (*India*).
Deshpande, Prabhakar Raghunath (*India*).
de Silva, Gostinnawadu Francis (*Ceylon*).
Dotivala, Hormuz Dadabhai (*India*).

* See page 228.
† This list also includes candidates who are exempt from, or who have previously passed, a part of the Examination and have now passed in the remaining subjects.

Passed—*continued*

Downey, James Arthur (*Australia*).
Gardiner, John Henry (*New Zealand*).
Gejji, Ramchandra Krishna (*India*).
Hayward, Doyle Walton (*South Africa*).
Homersham, Brian Ryder McClintock (*New Zealand*).
Hussain, Lewis Emmanuel (*India*).
Iengar, Naduvakkarai Srinivasa Aravamuda (*India*).
Jangalwala, Dara Dinshawji (*India*).
Jones, Harold Alan (*Australia*).
Karve, Keshav Raghunath (*India*).
Khanna, Chaman Lal (*India*).
Krishnaswamy, Vippodu (*India*).
Lodge, Ernest Charles (*South Africa*).
McGill, John Stirling (*South Africa*).
Mahajan, Narayan Balwant (*India*).
Melville, Denis Hill (*Malta*).
Mohanraj, Vellore Govindraj (*India*).
Murthy, B. N. Sreenivasa (*India*).
Pattison, John Charles (*South Africa*).
Pearson, John Archibald (*New Zealand*).
Pereira, Charles Anthony Frideswide (*India*).
Ramanathan, P. (*India*).
Rane, Kumar Shridhar (*India*).
Rao, Basrur Venugopal (*India*).
Russell, Ernest Sidney (*South Africa*).
Sankaran, Venkatram (*India*).
Seervai, Homi Pirojshaw (*India*).
Sivasamban, Palayavalam Sivaramier (*India*).
Soman, Narayan Shridhar (*India*).
Srinivasan, K. (*India*).
Srinivasan, Kazhiur (*India*).
Sukhadia, Pratapchandra Uttamram (*India*).
Thomas, Ambrose Bramwell (*India*).
Thombre, Balkrishna Vithal (*India*).
Toma, Robert (*Egypt*).
Treasurer, Vinaykant Dhirajlal (*India*).
Vanikar, Balkrishna Sakharam (*India*).
Vohra, Satya Pal (*India*).
Wagle, Moreshwar Mangesh (*India*).

Passed Part I only

Anderson, James Robert (*New Zealand*).
Bapat, Waman Vinayak (*India*).
Bhagawat, Sadashiv Ramachandra (*India*).
Bhatnagar, Sharda Bhushan (*India*).
Blakeley, Philip William (*New Zealand*).
Canning, Randall George (*South Africa*).
Churchill, John Henry Castleton (*South Africa*).
Cooray, Nawalage Justin (*Ceylon*).
Crozier, Ian Vernon Claude (*Ceylon*).
Dissanayake, Sirisena (*Ceylon*).
Downey, Raymond Sinclair (*Australia*).
Francis, Edward Charles (*Australia*).
Geoghegan, Joseph Francis (*New Zealand*).
Ghosh, Nikhil Krishna (*India*).
Goverdhan (*India*).
Griffith, William Henry Deane (*South Africa*).
Halliday, Kenneth William Jardine (*South Africa*).
Lake, Arthur Lawrence (*South Africa*).
Lele, Vyankatesh Govind (*India*).
Mathiesen, Eric (*South Africa*).

Passed Part I only—*continued*

Menty, Burjor Manchersha (*India*).
Page, Ian Marshall (*New Zealand*).
Raj, Cathiresam Pillai Mathava (*Ceylon*).
Rajagopalan, Subrahmanya (*India*).
Ramaswami, K. (*India*).
Rao, Guthikonda Virabhadra (*India*).
Reddy, S. R. Vithoba (*India*).
Rose, Raymond (*South Africa*).
Sarma, P. R. Neelakanta (*India*).
Seethapathirao, Devaguptapu (*India*).
Shah, Nagindas Vithaldas (*India*).
Shah, Shantilal Amarchand (*India*).
Shankaran, Alladi (*India*).
Srinivasan, Raghavachari (*India*).
Steele, Harry Theodore (*South Africa*).
Subrahmanyam, P. Ch. (*India*).

Passed Part II only

Alagaratnam, Candiah (*Ceylon*).
Carrier, Mervyn Joseph Alexander (*Federated Malay States*).
McArthur, Roy Frederick (*New Zealand*).
Mouat, William Neils (*New Zealand*).
Muthalaly, K. N. Abraham (*Federated Malay States*).
Tote, Balmukund Sayanna (*India*)

ELECTIONS AND TRANSFERS

At the Ordinary Meeting of The Institution held on the 7th April, 1938, the following elections and transfers were effected:—

Elections

Member

Braillard, Raymond.

Associate Members

Benstead, Charles Grey, B.Sc.Tech.
Bray, Frederick Harry.
Cochrane, John Noel, B.Sc.
Costin, Arthur William, B.Sc.(Eng.).
Emery, Wilfred Daniel, B.Sc.
Gough, Kathleen Agnes (Miss), B.Sc.
Hargreave, Ernest.
Holt, Frederick Brereton.
Hughes, Cecil, B.Sc.(Eng.).
Lavington, Edgar.
Lindsay, Charles George.
Lloyd-Jones, Maurice Glyn, B.Sc.
Lumsden, Robert Smith.
Mill, Harry.
Mitchell, Percy George.
Pattison, Raymond.
Pestarini, Joseph Maximus, Prof., Dr.
Reynolds, William John, B.Sc.
Saville, Willie.
Sharpe, Hubert Thomas A.
Starkey, Henry Yorke.
Stonebanks, Arthur Mayhew.
Wain, Thomas Henry M., B.E.
Wallis, Herbert.
Watson, Thomas.

Associates

Drummond, George Valentine.
Fullerton, Leo Lewis.
Longthorne, Joseph.
Maddocks, James.
Seaton, John Howard.
Wilson, William Humble.
Wiltshire, George Reginald.

Graduates

Beattie, Robert Kyd, B.Sc.
Booth, Reginald Wentworth, B.Sc.
Broad, Ewart Richard, B.A.
Brown, Francis James, B.Sc.(Eng.).
Burnet, James.
Chakrabarty, Manindra Nath, B.Sc.
Colles, William Morris, B.A.
Copping, Geoffrey Percy, B.Sc.
Duncombe, Eliot, B.A.
Dezsoe, Heinz K.
Eraut, Alexander Dennis, B.A.
Evans, Reginald David, B.Sc.
Gable, Thomas John.
Guthrie, Duncan.
Heal, Henry Thomas.
Hicks, George Herbert B., B.A.I., B.A.
Hinckley, Roy Thomas.
Horn, James Gordon, B.Sc. (Eng.).
Hubbard, Bruce Lancelot F., B.Sc.
Hussein, Mohamed Aly, B.Sc.(Eng.).
James, Harold Harley.
Johnson, Eric Weaver, B.A.
Karney, William Phillip.
Kekre, Madhusudan Nilkanth, B.Sc.
Lind, Charles Andrew R.
Nuttall, Harold.
Pirchan, Emil Edwin, B.E.
Sanderson, Philip George.
Shackleton, Norman.
Taylor, Graham Sinclair, B.A.
Tonge, Frank.
Whitehead, John.
Whiteley, Trevor, B.Sc. Tech.
Woodbridge, George Lashmar, Lieut.-Commander, R.N.(Ret.).

Students

Adhikary, Phanindra Mohon.
Almond, Herbert.
Anderson, Wilfred Roy.
Arjuna, Megh Raj.
Atkinson, Alan.
Bakeroff, Habib Khamsi.
Bartlett, Peter Malcolm.
Bell, Walter.
Bennett, William Gordon.
Bentley, Donovan Vernon C.
Blake, Peter Maurice.
Blunden, Frederick Charles.
Boulton, Brian.
Brown, Leslie Ronald.
Chugani, Gurbux Kodumal.
Cook, Albert Trevor.
Cranage, William Walter.
Dasgupta, Shib Sundar.
Davies, Harold.
Deeley, Reginald Ernest.
de Palo, Walmer Louis V.
Deshmukh, Giridhar Trimbakrao.
el Messiri, Mohammed el Anwar A.
Else, William Alan.
Fisher, Charles Arthur.
Fletcher, Stuart.
Forsythe, George Andrew.
Green, Richard Douglas.
Green, John.
Griffiths, Ronald Bertrand.
Hasluck, Norman Edwin.
Hickling, Charles Geoffrey.
Holloway, Leonard George.
Holtom, Gordon Mark.
Hoon, Hari Krishen.
Hughes, David Alexander.
Ingham, Percy.
Jafferjee, Asgarali.
Jaques, Sidney Herbert.
Jones, Edgar Goldstone.
Kesari, S.
King, Charles John.
Kington, Cecil Newton.
Knowlson, William John.
Lal, Girdhari.
Lee, Chih-Wu.
Levin, Arthur.
Little, John.
Lomas, Wright.
Macnab, William Theodore.
Marfakia, Jimmy Kaikhusroo.
Martin, Stanley Arthur.
Menon, Bhakti Vilas D.
Mitra, Asok Kumar.
Morris, Islwyn.
Morris, Harold Thomas.
Moss, Richard Allen S.
Napper, Charles Geoffrey.
Oliver, Albert Jackson.
Parsons, Alfred Lorenz.
Pé, Aung.
Pearce, Raymond.

Students—continued

Pedley, William.
Perry, Harold Leslie.
Quinn, Joseph Francis.
RamaMurty, Nelamangala Vuddi S.
Ramanathan, G.
Reynolds, William Charles.
Richardson, René Joseph.
Roberts, Denis Norman.
Russell, Raymond Harry.
Ryder, Melville Francis.
Satyanarayana, Nimmagadda.
Shafy, Morad Abdel.
Smith, Geoffrey Foster.
Spencer, Arthur.
Stille, Carl Erik.
Stockell, Cyril John.
Surtees, Benjamin John.
Subbarao, Vankina.
Sweet, Alexander.
Tidey, Laurence Charles.
Tonse, Surendranath Pai.
Topping, George Edward.
Townsend, William Charles G.
Tweedy, Stanley Edwin.
van Gelder, Frances Marguerite A. (Miss).
Viswanathan, W.
Walker, John Basil.
Walker, Maurice Frederick.
Watt, Thomas John.
Watts, Frederick Albert.
Warden, Frederick William.
Weston, Hugh Sydney M.
Willson, Geoffrey James.
Wilson, Donald Mervyn.
Windows, Clifford Edgar.
Winter, Ronald Sidney.

Transfers

Associate Member to Member

Blackburn, Charles Lord, B.A.
Clotworthy, Stanley Edward, B.Sc.(Eng.).
Egginton, John Leslie, B.Sc.
Ellis, Thomas, B.Sc.
Horrell, Lloyd Leslie
Knight, Henry de Boyne, B.Sc.
Lovely, William Stanley, B.Sc.
McLeod, Hugh Henry.
Rodger, John Wilfred.
Sayers, Donald Phillpott, B.Sc.
Scutt, William Duke.
Sinclair, George Flett.
Taylor, Eric James.

Associate to Associate Member

Blagg, Sydney Moody.
Breckell, Henry.
Burton, Edward Arthur.
Williams, John William M.

Graduate to Associate Member

Barton, Charles Henry.
Colvin-Smith, Peter Molison.
Doshi, Jagjivandas Hiralal.
Ellis, Horace Dudley McD., M.A.
Farries, Herman Ramsay, B.Sc.
Finch, Frank Hugh U.
Fowlie, William Stephen.
Gorrie, William Campbell, B.Eng.
Inglis, Felix Stevens.
James, Griffith Alcwyn.
Knott, Harry Cleal.
Lejeune, Sydney Maurice.
Lester, Guy Cyril O.
Mathur, Lakshmi Narain, B.Sc., B.Eng.
Metcalf, Alfred Guest, B.Sc.
Price, Trevor Gwyn E., B.A.
Raahauge, George Alfred.
Richards, Charles Graham, M.Sc.Tech.
Robinson, William George, B.Sc.Tech.
Smith, Walter William, B.Sc.
Stanton, Eric Percy, B.Sc. (Eng.).
Stewart, Franz Schubert, B.Sc.
Stubbs, William.
Taylor, Leonard Francis, B.Sc.(Eng.).
Thomas, Harry.
Thomson, William Sidney, B.Eng.
Turner, Herbert Alexander, B.Sc.(Eng.).
Vines, Murray.
Walker, Thomas Henry, M.Eng.

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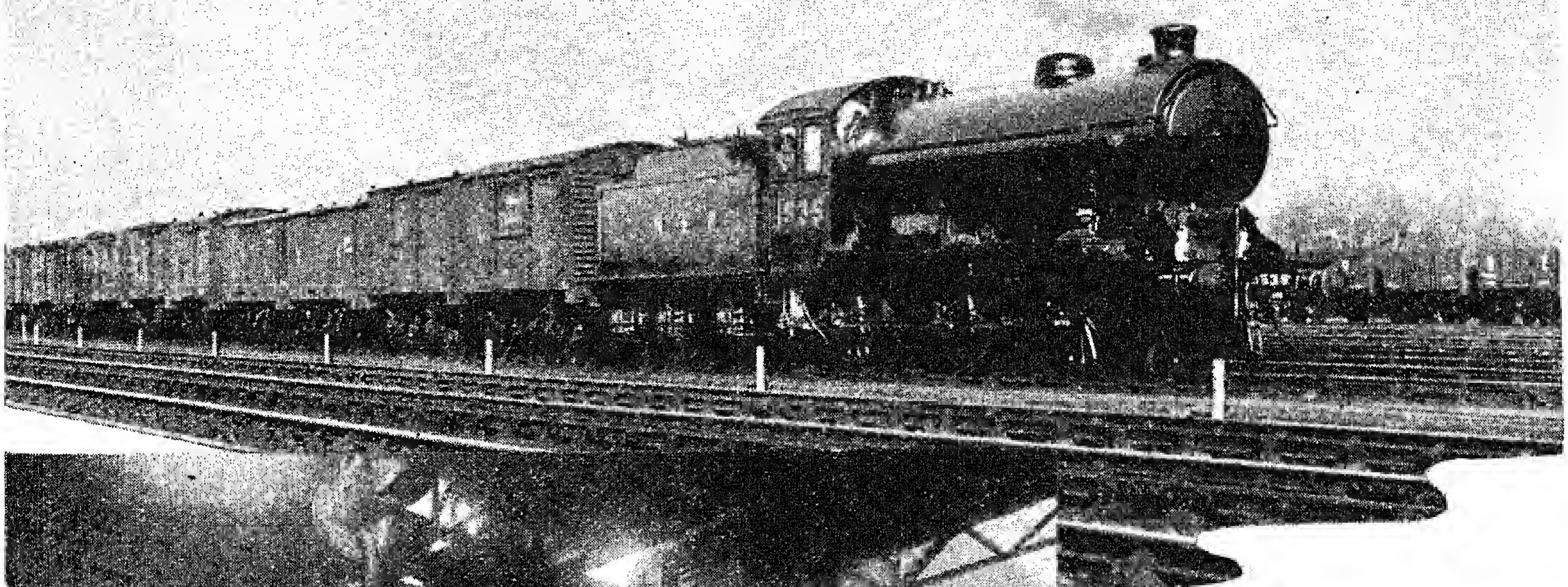
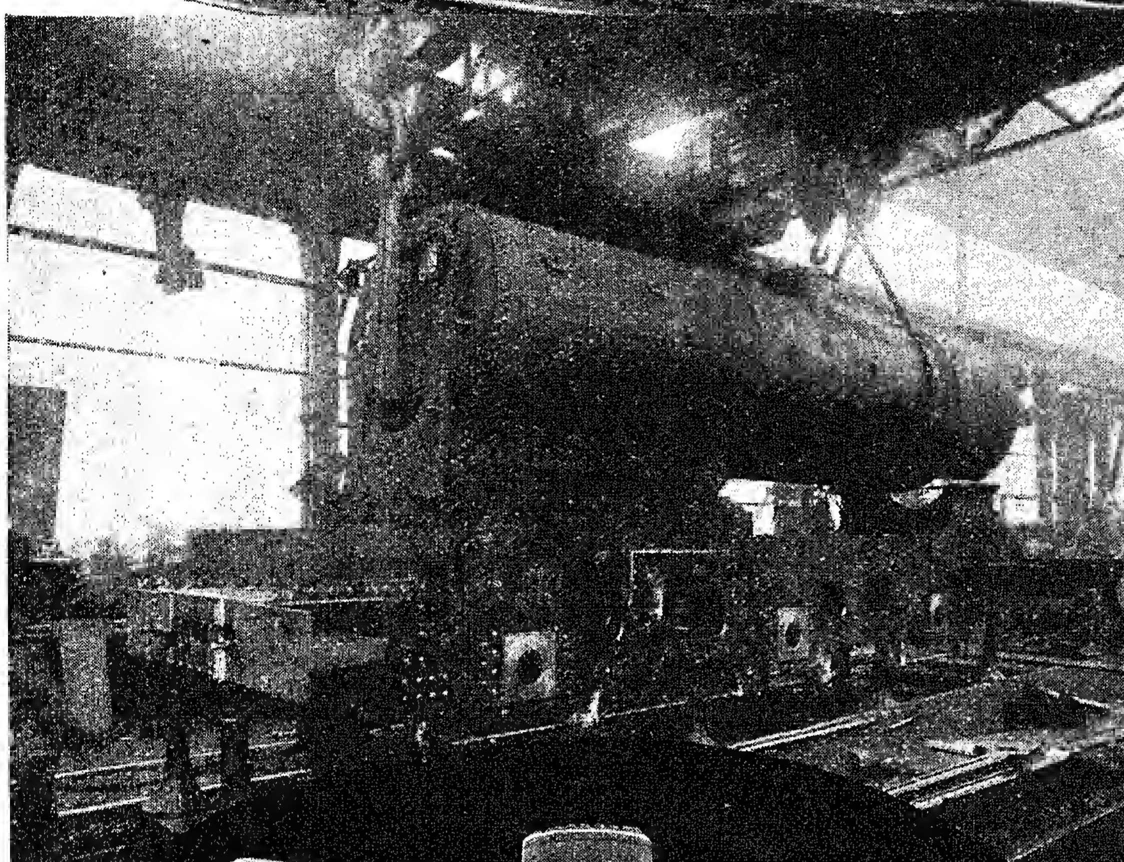
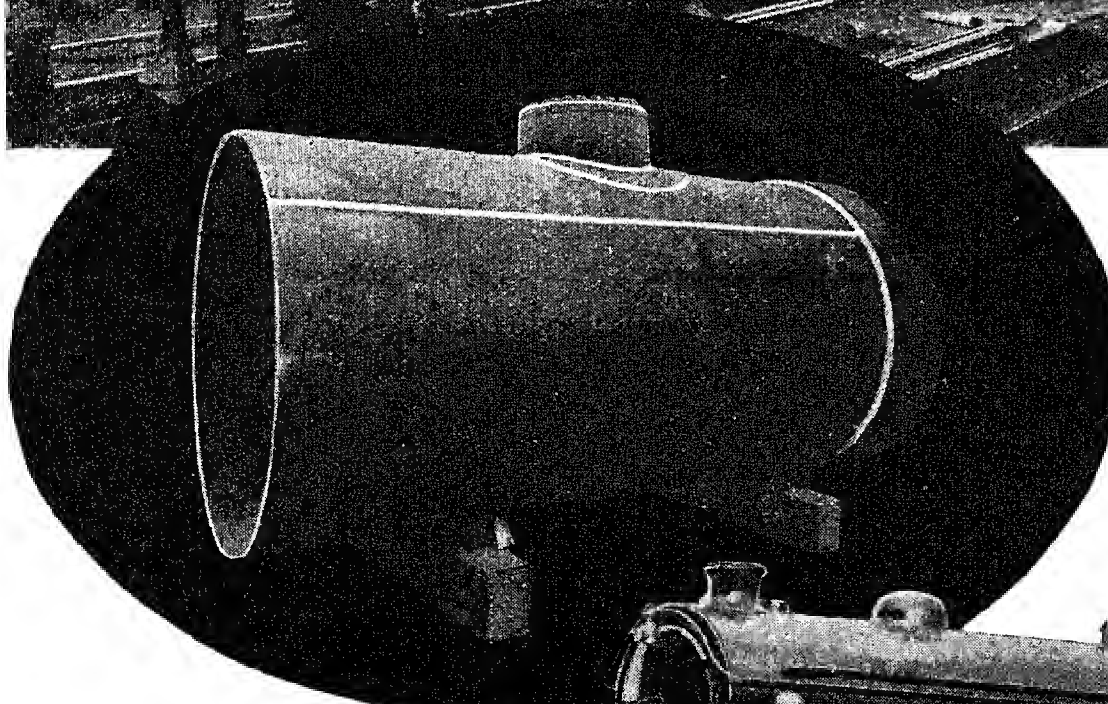




L.N.E.R. Locomotives Nos. 1509 and 1535 were turned into traffic early in 1938, in the North Eastern Area. Known as J.39 Class Locomotives, they are designed for fast goods and special passenger service and are of particular interest as the boiler barrels are constructed by the Babcock Class One Fusion Welding Process, and as such represent one of the first orders for these welded pressure vessels for use in England. The barrels are 5′ 6″ outside diameter x 9′ 8″ long and designed for a pressure of 180 lbs. per square inch. Three such barrels were constructed. The illustrations show the welded boiler barrel, the complete boiler being lowered into the frame in the erecting shop, and the finished locomotive.



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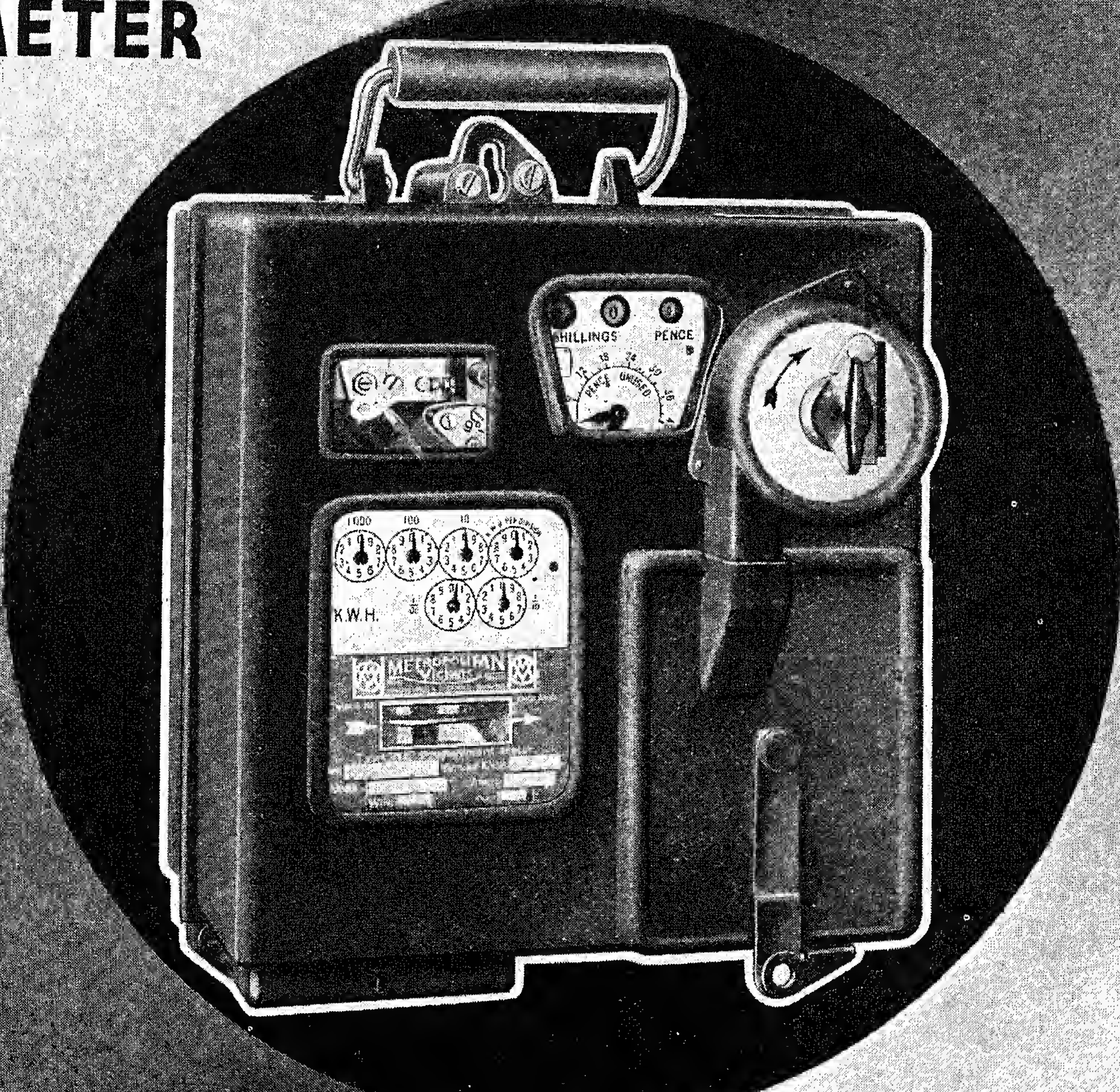

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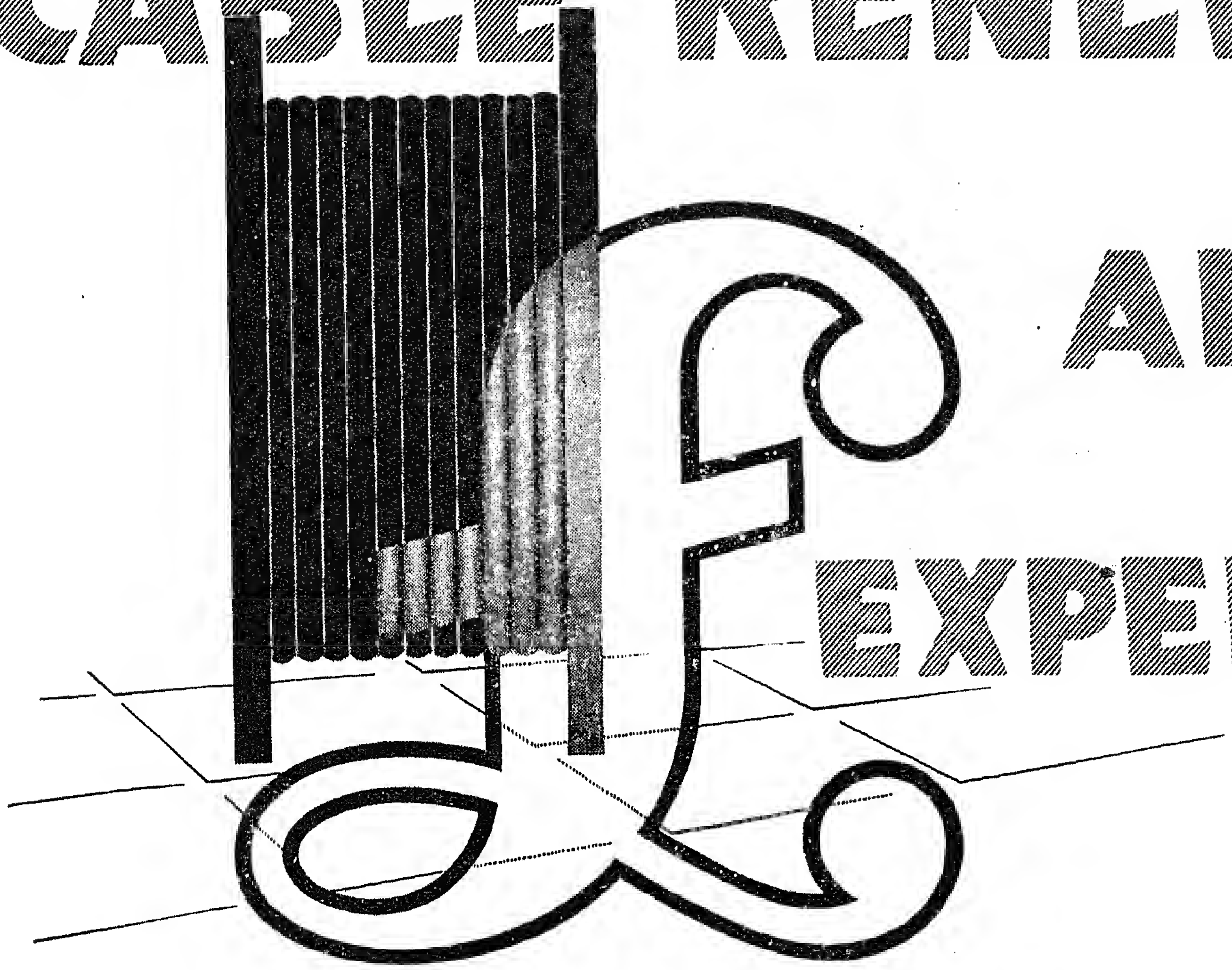

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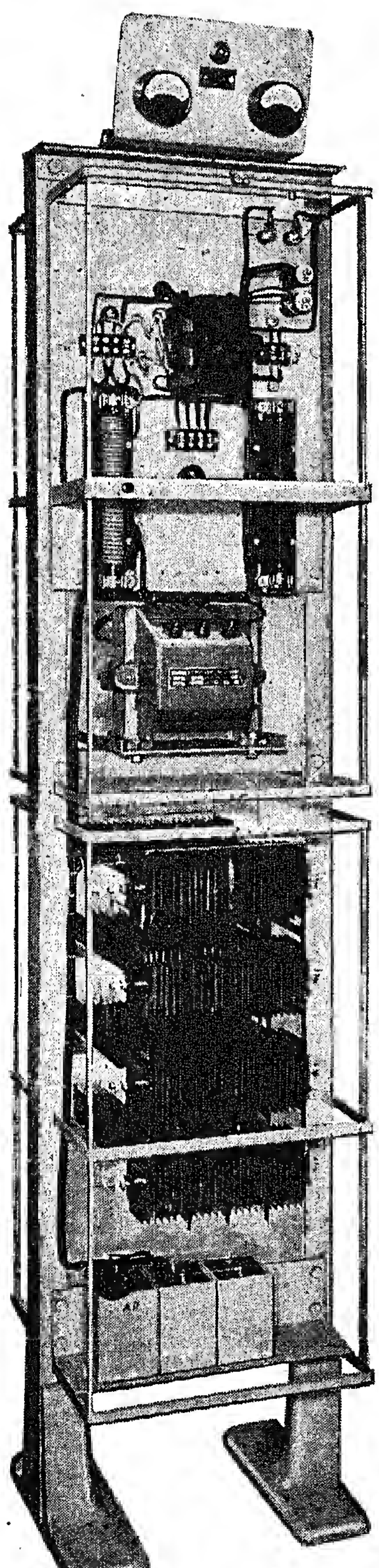

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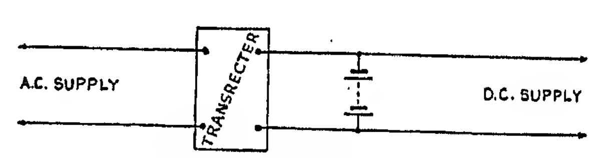

Diagram of connections

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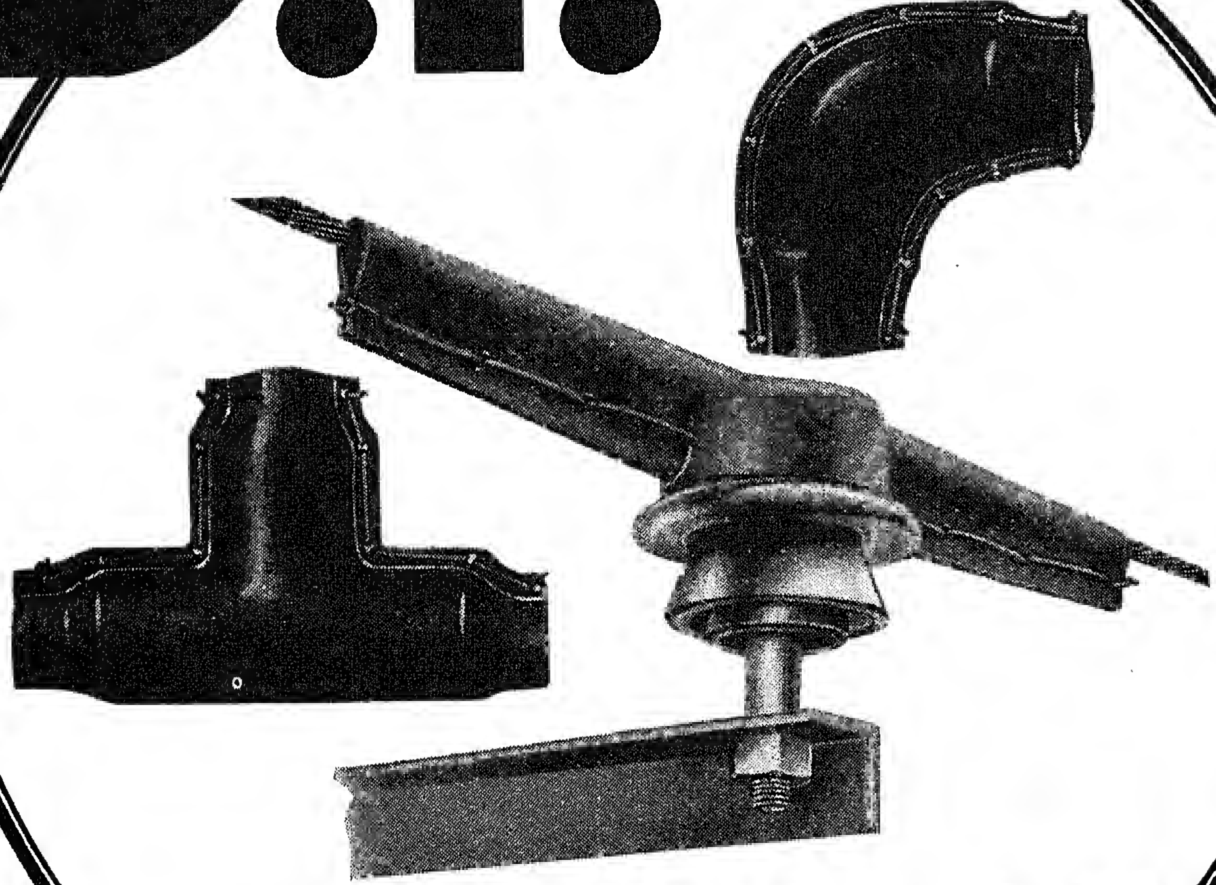

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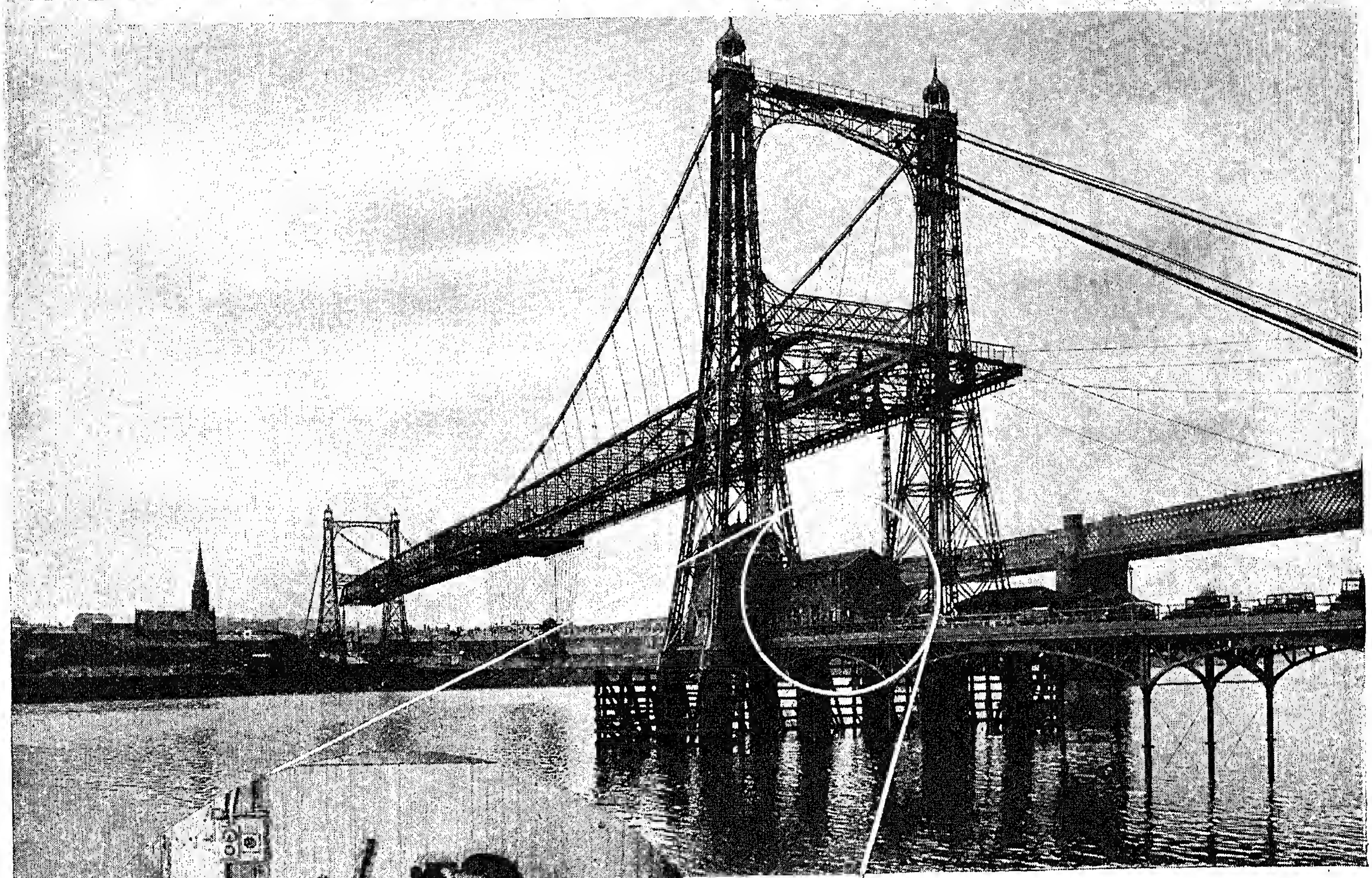

The inset picture shows the G.E.C. alternating current Welding Set used for the welding of suspension straps for this bridge.

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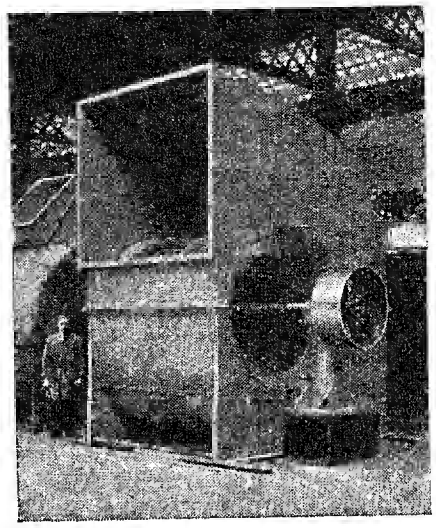

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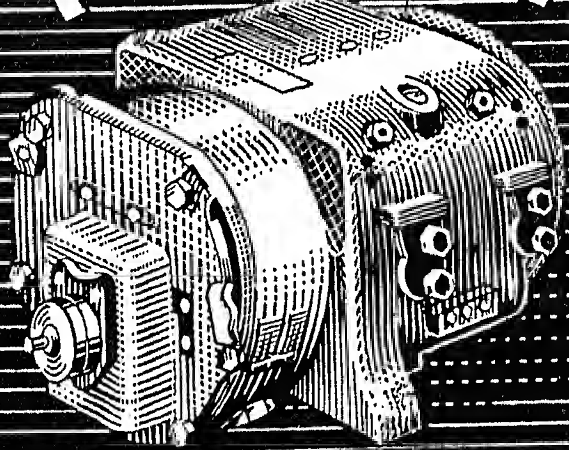

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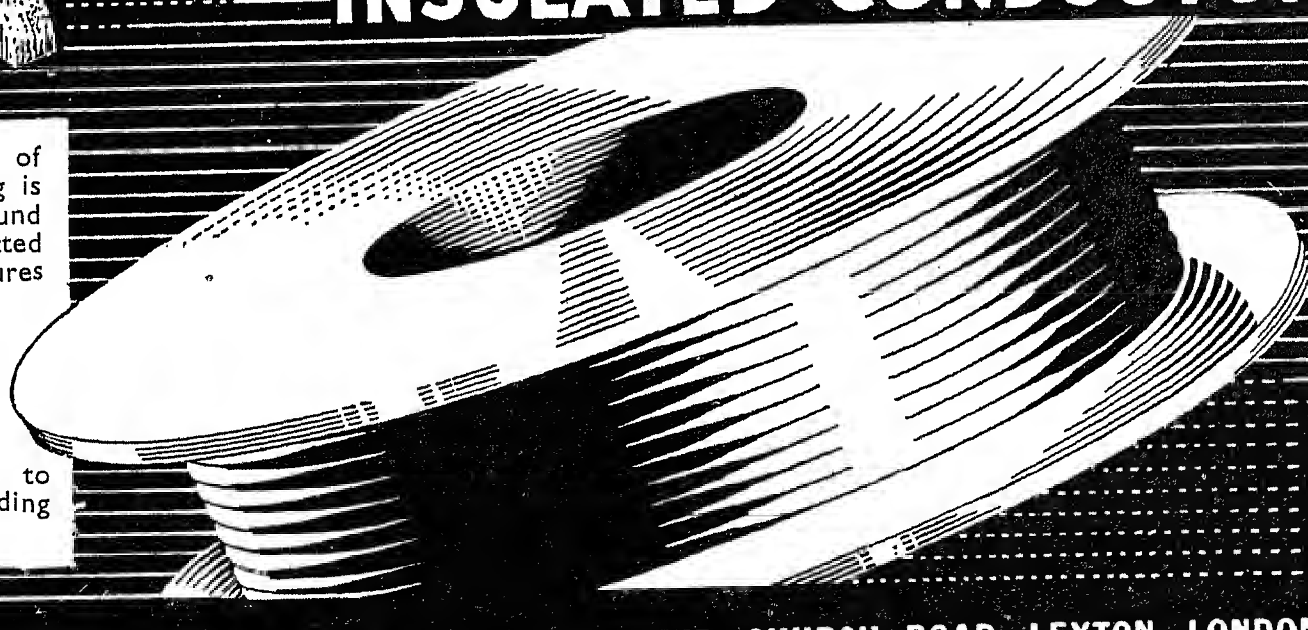

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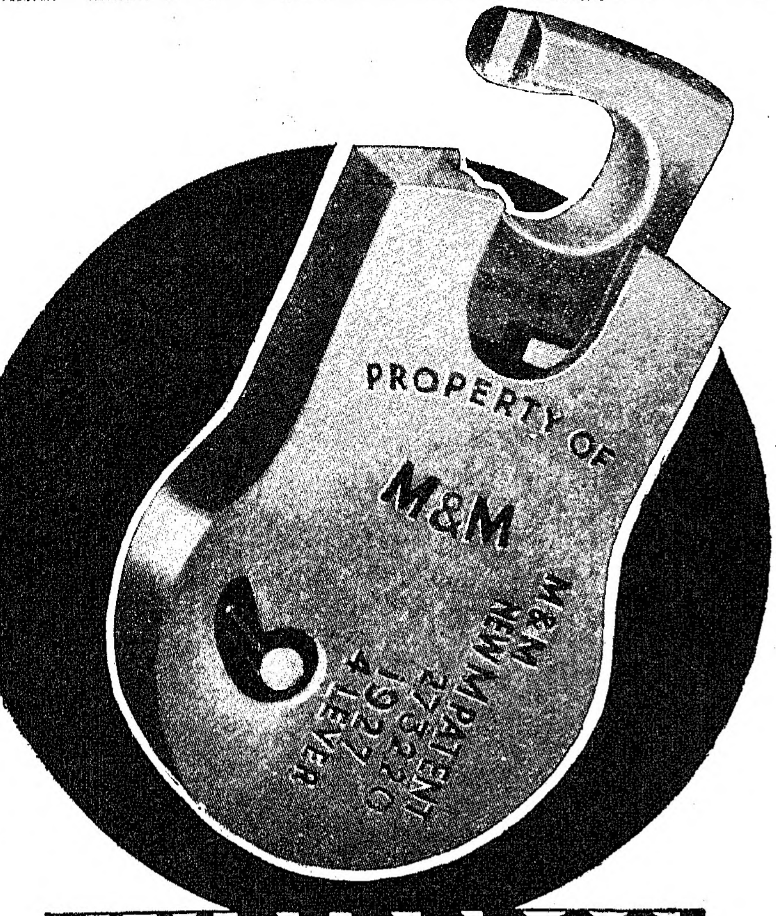

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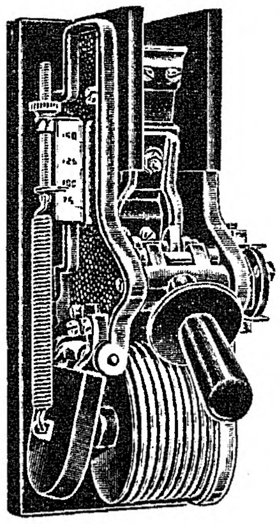

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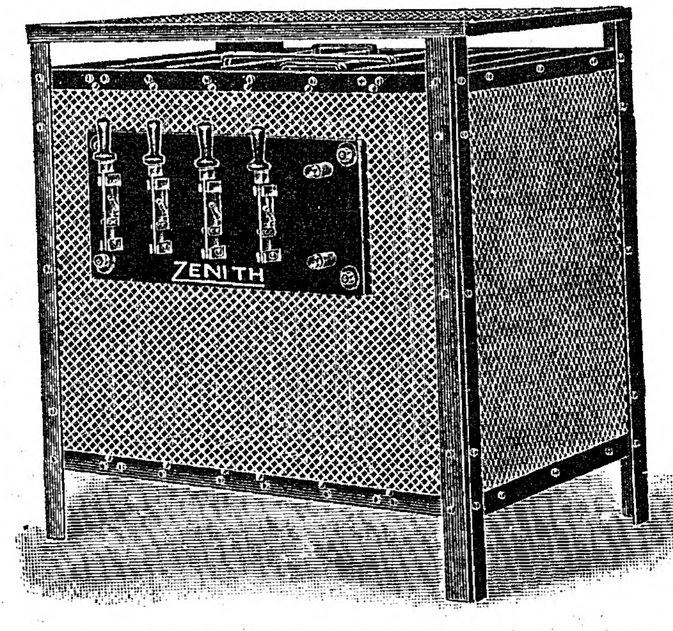

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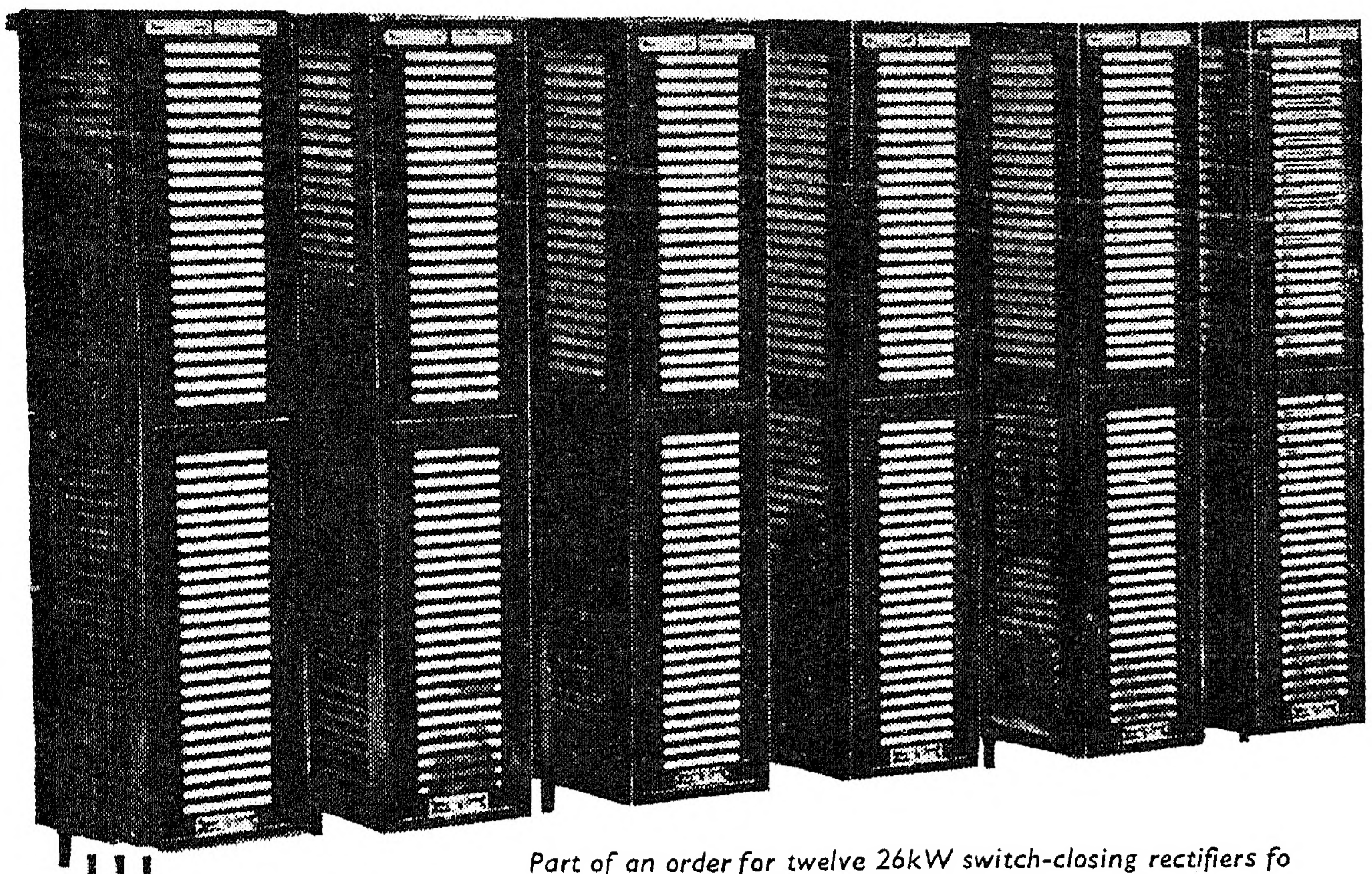

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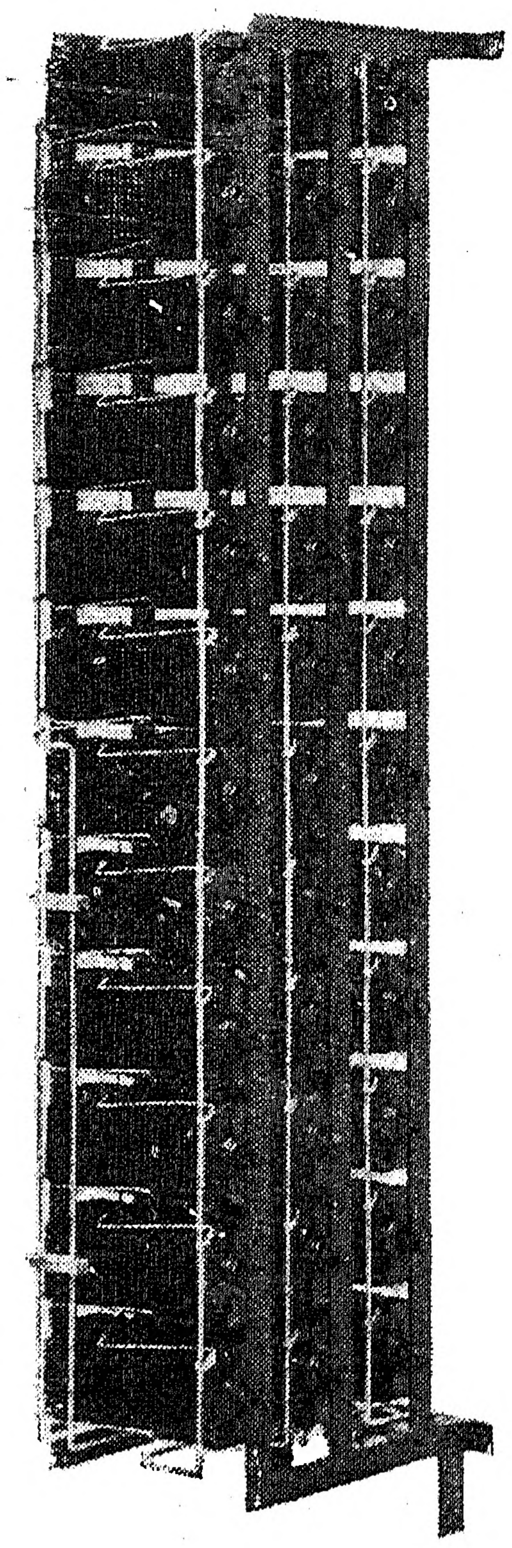

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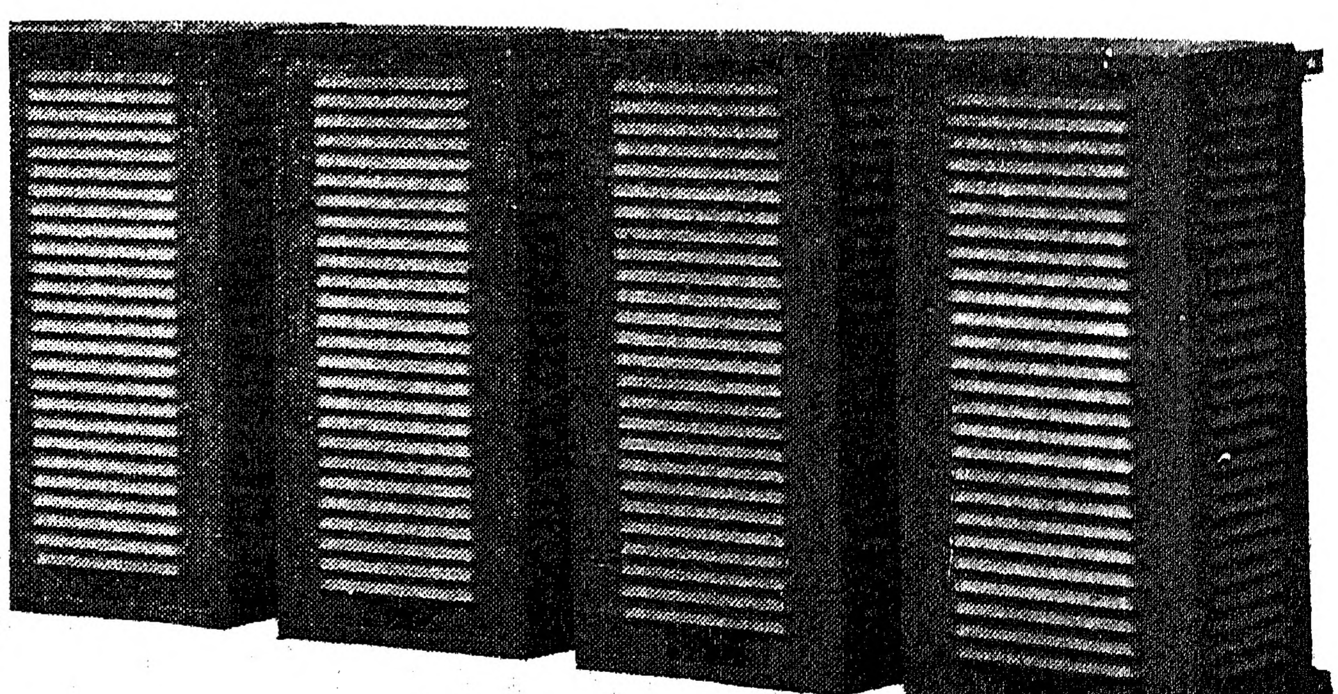

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